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DESIGN AND EVALUATION OF A SINGLE-INLET PULSE DETONATION COMBUSTOR

by

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June 2011

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Pulse detonation combustion offers thermodynamic advantages to the next generation of combustion systems. The thermodynamic efficiency is substantially improved over constant-pressure combustion systems by utilizing detonation-based combustion that occurs typically between 40 and 60 pulses per second. An existing four-inlet combustor was modified to a single-inlet arm design for integration with a rotary-valve concept. This paper discusses the design process of the single-inlet combustor so that it provides the same operation and reliability characteristics as its four-inlet predecessor. The design was derived from analysis through Computational Fluid Dynamics (CFD), which compared a variety of single-inlet arm designs to the four-inlet model. Cold flow analysis was achieved with ANSYS CFX software to map the flow field through the combustor. The combustion features inside the engine, were predicted with ANSYS FLUENT software. The inlet dump angle and ignition-shroud were selected from the results in order to support the optimal environment for flame kernel growth and subsequent deflagration to detonation transitions. After completion of computer modeling and analysis, the successful design was manufactured and assembled for testing.

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DESIGN AND EVALUATION OF A SINGLE-INLET PULSE DETONATION COMBUSTOR

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Pulse detonation combustion offers thermodynamic advantages to the next generation of combustion systems. The thermodynamic efficiency is substantially improved over constant-pressure combustion systems by utilizing detonation-based combustion that occurs typically between 40 and 60 pulses per second. An existing four-inlet combustor was modified to a single-inlet arm design for integration with a rotary-valve concept. This paper discusses the design process of the single-inlet combustor so that it provides the same operation and reliability characteristics as its four-inlet predecessor. The design was derived from analysis through Computational Fluid Dynamics (CFD), which compared a variety of single-inlet arm designs to the four-inlet model. Cold flow analysis was achieved with ANSYS CFX software to map the flow field through the combustor. The combustion features inside the engine, were predicted with ANSYS FLUENT software. The inlet dump angle and ignition-shroud were selected from the results in order to support the optimal environment for flame kernel growth and subsequent deflagration to detonation transitions. After completion of computer modeling and analysis, the successful design was manufactured and assembled for testing.

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LIST OF ACRONYMS AND ABBREVIATIONS

C2H4	Ethylene
CAD	Computer Assisted Drawing
CFD	Computational Fluid Dynamics
cm	Centimeters
DDT	Deflagration-to-Detonation Transition
K	Kelvin
kg	Kilograms
kg/s	Kilogram/second
m/s	Meters/ second
N	Nitrogen
NPS	Naval Postgraduate School
O	Oxygen
PDC	Pulse Detonation Combustion
PDE	Pulse Detonation Engine
s	Second
TPI	Transient Plasma Ignition

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I. INTRODUCTION

A. PULSE DETONATION COMBUSTION CYCLE

Detonation combustion inherently has a high thermodynamic efficiency due to a lower entropy increase of the working fluid for a given amount of heat release. Competitive systems that rely on the Brayton cycle, utilize deflagration combustion, which occurs under near constant pressure conditions. The effective release of energy by a detonation wave versus a deflagration wave allows a Humphrey cycle to produce more work than the Brayton cycle for the same energy release. Along with the increased performance, a Pulse Detonation Combustion (PDC) consists of relatively simplistic fabrication when compared to gas turbine engines (Nichols, 2010). Practical development of detonation-based systems therefore require repeated detonation of reactants hence the name PDC.

The PDC cycle occurs in six distinct stages as illustrated in Figure 1. Inaccurate timing of these stages may lead to non-detonation combustion, and could dramatically lower the efficiency of the combustion chamber cycle and system.

The PDC cycle begins by filling the combustion chamber completely with the predetermined mixture of oxidizer and fuel (Warwick, 2008). Ignition starts the deflagration event, which can come from a variety of sources. The deflagration wave then transitions to a detonation wave that travels down the length of the combustion chamber. As a result, expansion of remaining combustion products creates a blow down of the system that reduces the combustion chamber pressure to the refresh level. Finally, the chamber is purged with new air (Zittere, 2009).

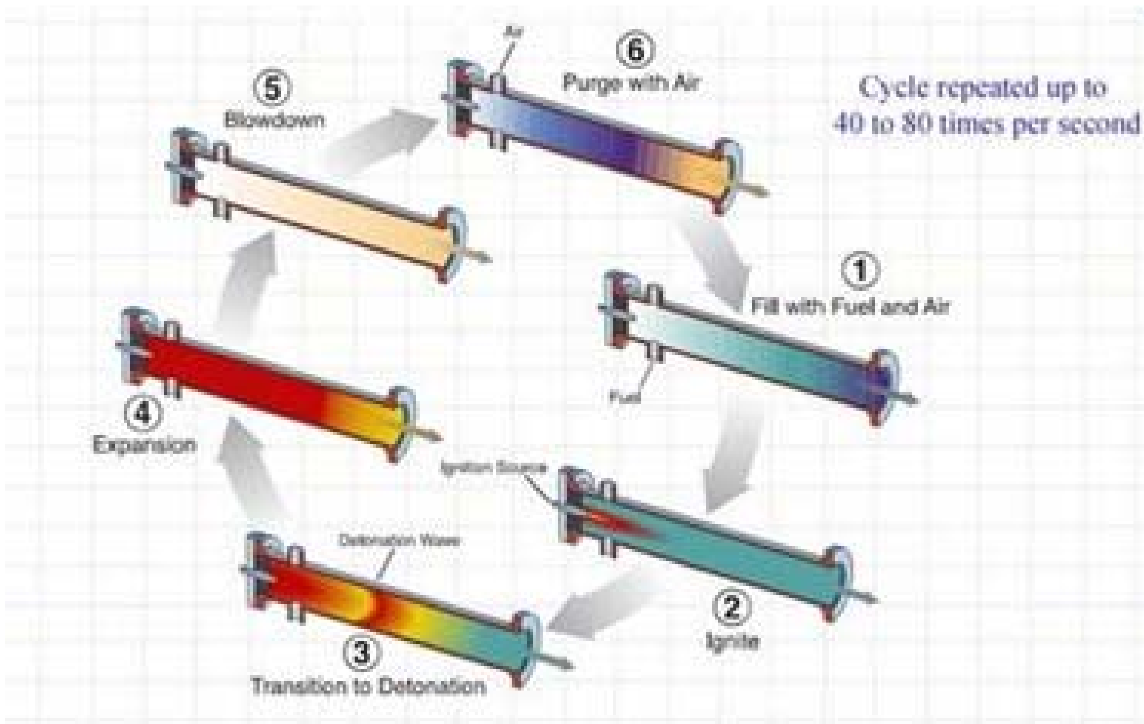

Figure 1. Pulse Detonation Engine Cycle (From Warwick, 2008)

B. COMBUSTION CHARACTERISTICS

The fundamental characteristic of a PDC is the ability to combust fuel through a detonation wave. Lee (2008) states that detonation requires that reactants remain ahead of the supersonic wave and an increase in density across the combustion wave. Without sufficient energy release to support a detonation wave, the combustion wave remains subsonic with respect to the reactants ahead of it; this is known as deflagration (Lee, 2008). The deflagration flame speed can be influenced by different mechanisms such as fuel distribution, variations, turbulence, mixture properties, and confinement (geometry). The design of a combustor can direct the subsonic wave as its disturbances move downstream and upstream propagation (Lee, 2008).

The design of the system will dictate how the transformation of deflagration-to-detonation transition (DDT) will occur. The design's intention will be to accelerate deflagration to a high supersonic velocity where the shock wave will abruptly modify to a detonation wave. This can be accomplished by methods such as the SWACER (Shock

Wave Amplification by Coherent Energy Release) mechanism in which chemical energy release is syncronized with shock pulses amplifyng the energy release (Lee, 2008).

C. APPLICATIONS OF PULSE DETONATION SYSTEMS

A few applications typically are considered when discussing the efficiency improvements of a PDC-based system. One such application is a supersonic air-breathing missile system that provides benefits including creating an ability to transport weapon payloads over longer distances for a given amount of fuel, increasing payload mass, or boosting block speed.

Power generation systems for shipboard use is another application being explored. Similar to diesel engines, PDCs have a high thermodynamic efficiency, but substantially larger power density due to the higher mass flow rates. The increased fuel efficiency could allow the surface Navy to reduce the fuel cost of generating shipboard power.

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II. BACKGROUND

A. BASELINE DESIGN

The existing PDC design is the result of development over nearly six years from a variety of graduate students at the Naval Postgraduate School. It consists of four-inlet arms that mix liquid or gas fuel with air prior to discharging into a single combustion chamber with a single ignition source. The most recent modification is the introduction of cooling to the combustion chamber using segments that are individually cooled by water. Their addition has allowed the PDE to run for 20 seconds at a time without having destructive heating issues. This design has proven to be effective in producing the conditions required to support detonations in the chamber.

Using air and ethylene as reactants, either a Transient Plasma Ignition (TPI) or a gas turbine plug is capable of igniting the mixture within the PDC. The current design utilizes four-inlets, converging with the center chamber that houses the ignition source and exit toward the left, as shown in Figure 2. The flow of air starts from the left and is mixed with ethylene at the gas injectors. There are also liquid injectors for JP-10, which allows for a modification to operate on practical liquid fuels. Restrictor plates are inserted into the four arms to isolate the upstream flow from the chamber pressure fluctuations (Dvorak, 2010).

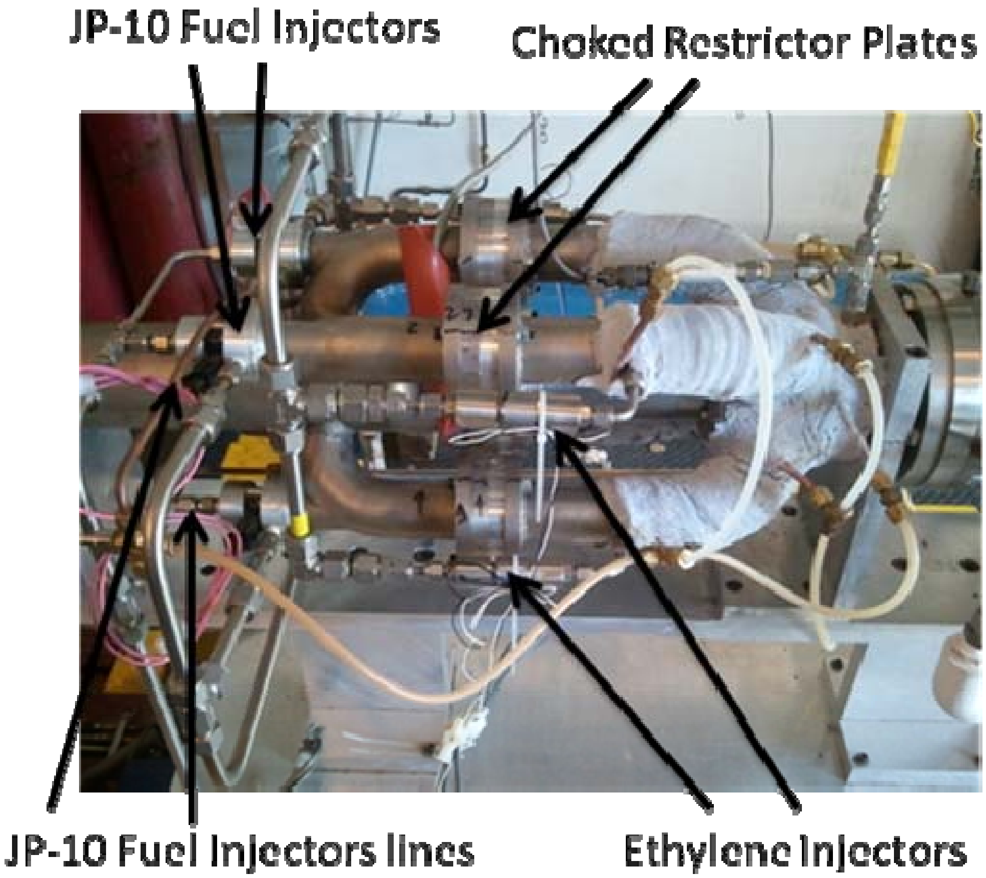

Figure 2. Design of Four-Inlet Arm System

While this rig is functional, it is impractical for future designs. For example, use of thrust vectoring for control would require three PDE chambers, which would require 12 inlets under this current design. Redesigning the system into a single-inlet therefore increases practicality. This research effort seeks the optimal design of a single-inlet PDE.

B. DUMP ANGLE

Converting the current four-arm inlet arm system into a single-arm inlet design required determining the optimal angle for inlet intersection with the combustion chamber. In order to create reliable combustion, the angle needs to produce recirculation zones that can support proper flame development. Using Computational Fluid Dynamics (CFD), Zittere (2009) evaluated three inlet dump angles of 30^{o}, 45^{o}, and 60^{o} to determine which would produce the most desirable recirculation zones. While all angles provided some recirculation zones, Zittere (2009) indicates that flame development is best facilitated when in conjunction with the position of the TPI/shroud in a head-end section design. The head end shape displayed in Figure 3 describes the analyzed sections.

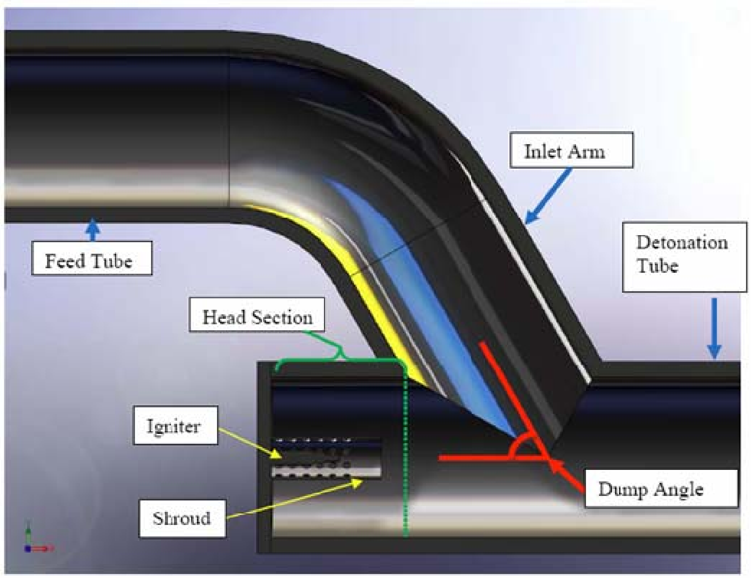

Figure 3. Head End Geometry for Four-Inlet Arm System (From Zittere, 2009)

Hawkes' (2009) physical experimentation validated the CFD analysis. However, due to manufacturing constraints, only angles of 45^o, 60^o, and 90^o were used. Testing examined the three different configurations at a variety of equivalency ratios (1, 1.2, and 1.5). Hawkes (2009) determined that a 90^o angle inlet caused the flame to become unstable and sometimes quench. Further experimentation showed that the 60^o angle inlet was best if the design required a large range of operational equivalence ratios. Ultimately, Hawkes (2009) concluded that a 45^o angle inlet provided the fastest ignition, and was successful at developing the growth of a flame.

C. FLAME DEVELOPMENT

The previous inlet angle evaluations helped to identify effective methods to create recirculation zones that facilitated healthy flame growth. This is promoted by protecting the spark created from the TPI from the use of a porous shroud developed and used on multiple NPS PDE designs; Hawkes' (2009) design is no different. Employing a high-speed camera facilitated observations of flame characteristics. Hawkes (2009) indicated a 45^{o} single-inlet permitted reactants to flow through the shroud and successfully ignite. While there, it becomes turbulent and rapidly spreads until exiting through small holes of the shroud on the opposite side of the inlet (Hawkes, 2009). This process is demonstrated in Figure 4.

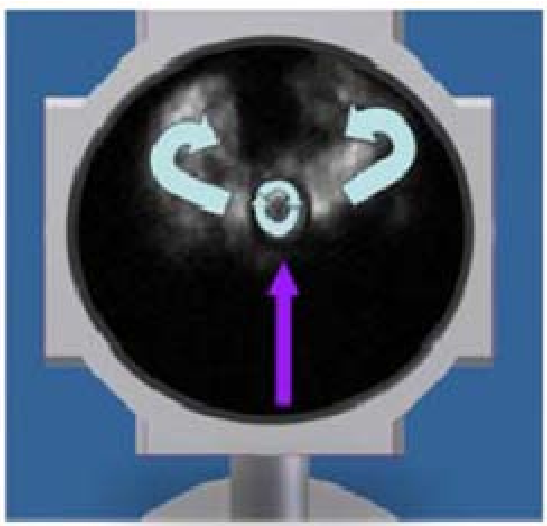

Figure 4. Flame Spreading Pattern for Single-Inlet Arm Design (From Hawkes, 2009)

D. SINGLE-INLET APPROACH

Based on results from previous work, a 45^{o} angle single-inlet arm design using 37.5% fewer perforated shroud to surround the TPI was developed. Along with the physical design characteristics, the next evolution in the PDE system was to determine the inlet geometry as it entered the combustion tube. A design that promotes uniform fuel and air mixture and similar rapid flame development as the four-inlet arm system is required.

III. COMPUTATIONAL FLUID DYNAMICS

A. COMPUTER MODELING

Computational Fluid Dynamics (CFD) has been advanced by the need to model problems involving fluid mechanics and thermodynamics. While primary implementation of CFD focused on gas dynamics, its applications have expanded into areas including environmental engineering, chemistry, and medicine (Tu, Yeoh, & Liu, 2008). CFD offers multiple benefits and is frequently used as an economical tool to evaluate engineering options prior to committing significant investments of resources.

Two different flow solvers were employed in this study. ANSYS 13.0 is a software program suite consisting of computational modals for solving complex algorithms associated with fluid flow and structural analysis. The two programs within ANSYS that were heavily utilized in this study were ANSYS CFX and ANSYS FLUENT. Solidworks 2010, a third program, provided the ability to create the virtual 3-D geometries from which simulations and parts were generated.

B. ANSYS CFX

CFX, a general fluid dynamic modeling application of ANSYS 13.0, provided fluid flow analysis for a variety of geometries (ANYSIS CFX, 2010). Understanding the desired results for the single-inlet arm system required development of a solid model representation of the current four-inlet arm design. The CFX finite volume evaluation program used the geometry and solved for the velocity field throughout the inlet arms and combustion chamber. Since the four-inlet arm design consistently creates detonations, it became the datum for follow-on analyses.

1. Boundary Conditions

The Computer Assisted Drawing (CAD) program Solidworks was used to develop the geometries later imported into the ANSYS CFX. Due to the nature of the ANSYS CFX software, the geometric figure had to represent the fluid volume within the anticipated structural design. The diameter of the four-inlet arm design's combustion chamber is 7.62 cm and the diameter of each inlet is 3.81 cm, all entering at 45^{o} angles Figure 5 shows the four-inlet arm design with a short combustion chamber, the porous shroud surrounding the TPI, and a close up of the meshed TPI region.

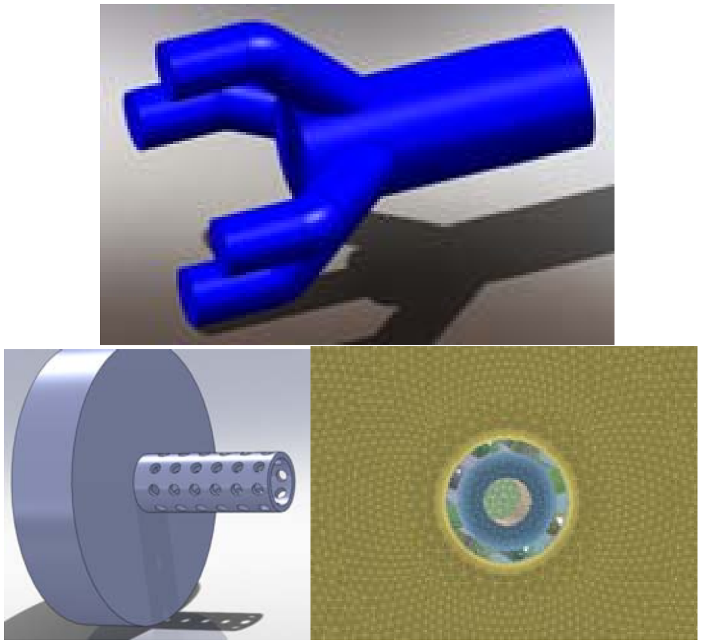

Figure 5. Design for Four-Inlet Arm System and Shroud

Descriptions of the settings used during the computational mesh development, as well as setup of initial conditions, are included in Table 1. The mesh details and resolutions of the inlet model were maintained for the single-inlet arm system. Element size was ascertained using a balance of both accuracy and length of time required to solve multimillion element solutions. The number of elements, 8 to 10 million, was determined to provide the needed accuracy without requiring each solution to utilize more than 16 processors on a Linux cluster for more than 4 to 5 hours.

Meshing Conditions			
Max Body Spacing	0.0011 mm	Angular Resolution	30^o
Min Edge Length	0.00011 mm	Max Edge Length	0.0011 mm
Inflation Layers	20	Expansion Factor	1.1
Min Internal Angle	5^o	TPI Inflation Max Thick	0.003 mm
Max External Angle	15^o	Nodes	1806324
Pyramids	3881	Prisms	205741
Tetrahedra	9637410	Total Elements	9847032
Boundary Conditions			
INLET		Mass Flow Rate	0.3125 kg/s
Flow Regime	Subsonic	Static Temperature	480 K
OUTLET		Mass Flow Rate	0.3125 kg/s
WALL		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
TPI Wall		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
INITIALIZATION		Pressure	1 atm
Material	Air Ideal Gas	Heat Transfer	Total Energy
Turbulence	k-Epsilon	Velocity u/v/w	0/0/60 m/s
Temperature	400 K	Intensity	Medium

Table 1. Preliminary Boundary Conditions for Four-Inlet System Cold Flow Analysis

Results of the CFX analysis, shown in Figure 6 show the fluid flow through the four-inlet arm system as black streamlines and the velocity magnitude as colored axial planes. The two streamline zones located at the head end of the combustion chamber reveal the desired recirculation zones for flame development. While the single-inlet arm design also produces recirculation zones, they can become too large. This results in long residence times for the combustion products and insufficient clearing of the chamber during the purge process, thereby causing auto ignition of the subsequent cycle.

In order to maintain similar residence timescales, the velocity distributions must remain near the same levels in the single-inlet arm designs. The cold flow enters the combustion chamber with an initial mass flow rate of 0.325 kg/s and resulting velocity inside the inlet arm reaches about 96 m/s, increasing roughly to 103 m/s prior to reaching the shroud located inside the chamber. As Figure 6 illustrates, the velocity inside the shroud ranges from 12 m/s near the inlets to 37 m/s in the center of the chamber. This can stifle flame development and, for this reason, the shroud needs to protect the flame.

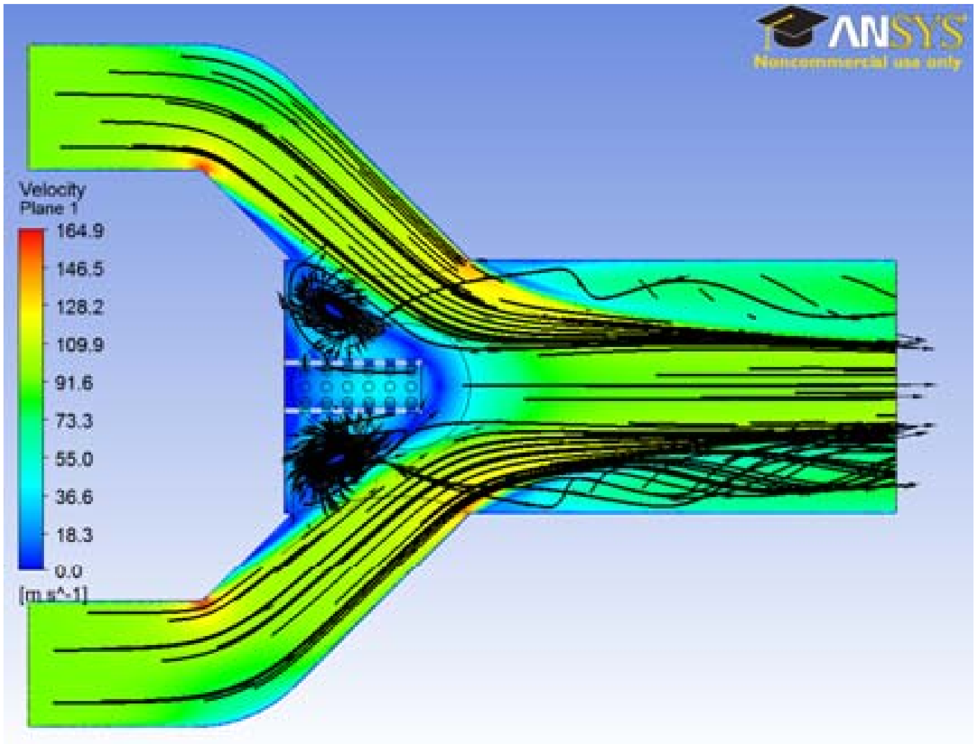

Figure 6. Fluid Flow With Velocity for Four-Inlet Arm System

The four-inlet results discussed previously provide characteristics that guide the proposed single-inlet design. Conditions for the single-inlet arm design are summarized in Table 2.

Inlet Velocity	~ 95 m/s
Velocity entering combustion chamber	~ 105 m/s
Velocity at bottom of shroud	~ 13 m/s
Velocity at center of shroud	~ 36 m/s
Recirculation zones (4)	~ 19-35 m/s

Table 2. Summary of Desired Cold Flow Conditions for Four-Inlet Arm System

2. Design Approaches

Zittere (2009) and Hawkes (2009) investigated three inlet dump angels, 45^o, 60^o, 90^o. The preferred inlet dump angle of 45^o and therefore this research aims to determine the optimal geometry. CFX analyzed the feasibility of several proposed alterations to the four-inlet arm system with respect to a single-inlet arm design: a centered two-inch inlet, a centered 7.62 cm inlet, a centered 2.54 cm inlet to 10.16 cm combustor, and a 3.81 cm inlet positioned offset from the middle. Three of the proposed inlet arm designs preserve combustion chamber entrance diameters of 7.62 cm for design uniformity of the previous PDC. Illustrations in Figure 7compare these proposed designs. Additionally, this view includes placement of the TPI shroud in the center of the inlet. This creates recirculation zones that occur near and in the shroud and allow for flame kernel growth. Included shrouds retain a 360^o porosity around the can, also similar to the originally design in Figure 5.

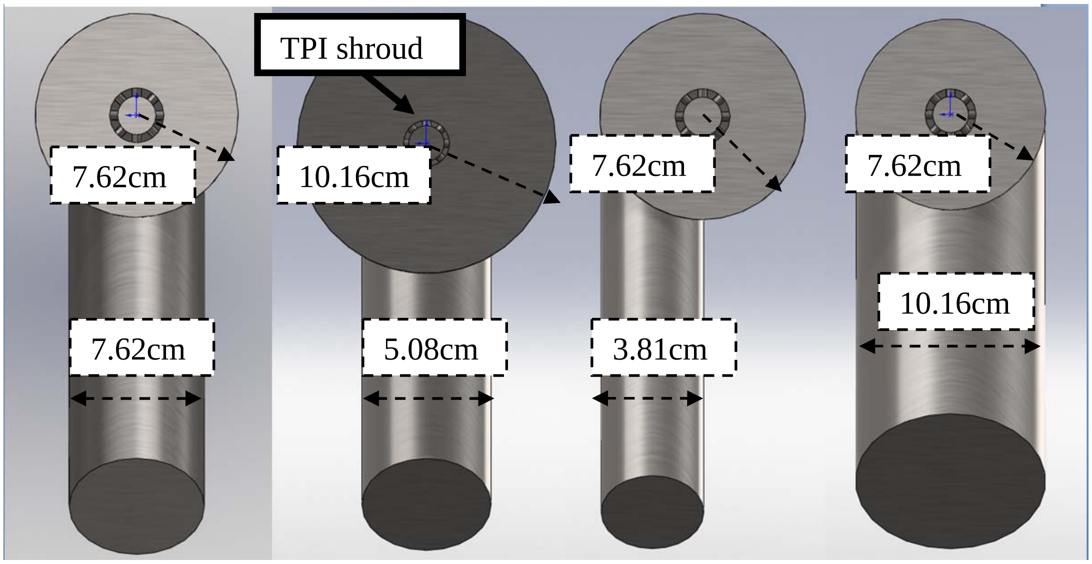

Figure 7. Comparison of Proposed Design Alterations

Initial analysis suggested reducing the number of holes in the shroud due to the high velocity introduced to the TPI, prompting the design of a less porous concept. A rendering of the two designs is included in Figure 8. Both images display a segmented area of the shroud and the blackened areas draw attention to the differences between the modifications. The cutout on the left in Figure 8 retains holes that surround the shroud a full 360^{o} while the cutout on the right demonstrates the modifications that only place holes in the top 180^{o}.

Figure 8. Comparison of Shroud Design With 360^{o} Holes and 180^{o} Holes

3. Design Assessment

The computational analysis investigated the reactant's velocity in each of the proposed designs. Special focus was placed on the reactant's velocity passing through the shroud in order to provide an environment conducive for ignition kernel development and subsequent flame growth.

a. The 5.08 cm Inlet Arm Into 7.62 cm Combustion Chamber

The illustration in Figure 9 shows the flow field for a 5.08 cm inlet arm entering a 7.62 cm combustion chamber. This proposed design revealed the existence of recirculation zones, however this design was abandoned due to its expected inability to allow proper flame development due to extensive velocities. Even though the location of the recirculation zone at the top of the head end portion of the combustion chamber is adequate for flame growth, the internal shroud velocities indicated in the results is unlikely to allow that the flame would develop enough to leave the shroud and enter the recirculation zone. As the flow enters the combustion chamber, the velocity of the reactants reaches values close to 209 m/s as they transit the inlet arm. This negatively affects flame development because it enters the shroud where the velocity ranges from 8 m/s to 103 m/s inside the shroud. While the lower values of this range are acceptable, the upper values would be too fast and likely cause flame blow out. Additionally, the velocity in excess of 150 m/s inside the chamber could also prevent the proper flame development. Ultimately, this design was abandoned and an alternate configuration was considered that possesses lower shroud velocities.

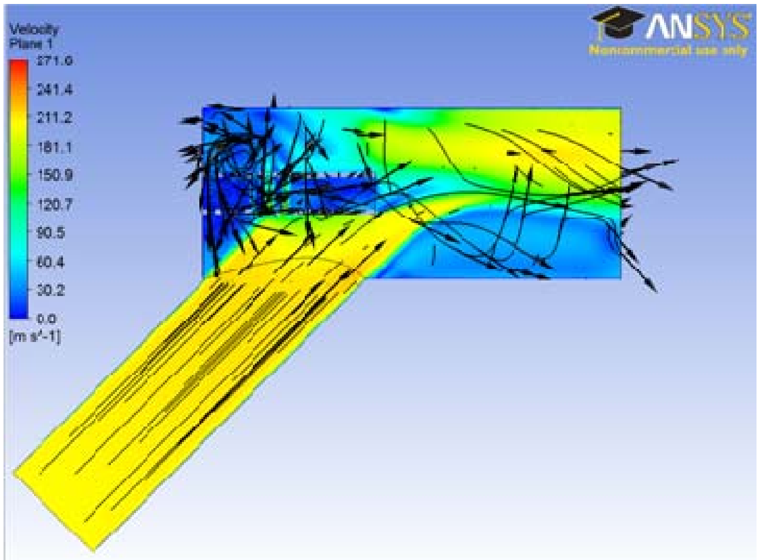

Figure 9. Fluid Flow With Velocity for a 5.08 cm Inlet Arm Into 7.62 cm Combustion Chamber

b. The 5.08 cm Inlet Arm Into 10.16 cm Combustion Chamber

The proposed design of a 5.08 cm inlet arm entering a 10.16 cm combustor chamber was also found to be unsuitable. This design provides for an additional recirculation zone to that of the previous proposed design, but the zone located at the head end of the chamber indicated a velocity between four and seven m/s, which was predicted to be too low and possess poor purge properties. This design also provided for a second zone closer to the opposing region, as demonstrated in Figure 10, with velocity more acceptable for flame development of nearly 25 m/s. However, its location was not conducive to this research since it did not work with the preferred location of the ignition source at the head end of the combustion chamber.

The velocity generated in this design is also unlikely to support healthy flame development. Although this geometry allowed the reactants to enter the combustor at nearly 176 m/s, the overall velocity inside the chamber remains in excess of 150 m/s. The decreased inlet arm velocity improved the velocity inside the shroud to a range of 12 to 42 m/s. Unfortunately, the recirculation zones contribute to areas of drastic differences in velocities to effectively create a sheer layer that the flame would likely be unable to penetrate. This secondary consideration regarding inhibited flame development throughout the chamber led to this design also being abandoned.

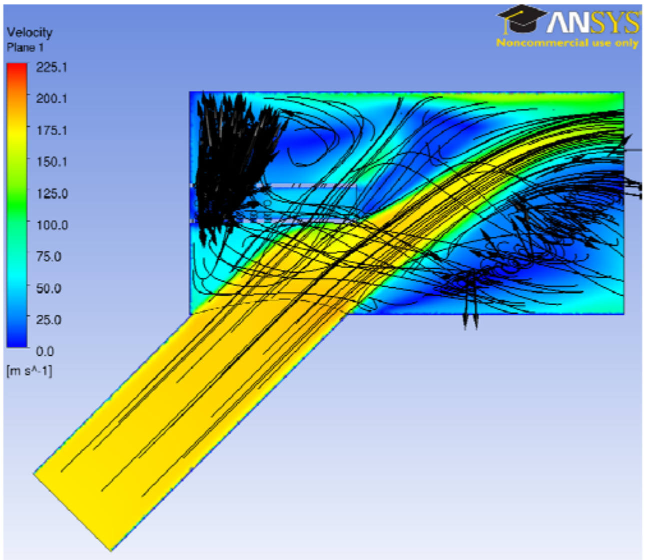

Figure 10. Fluid Flow With Velocity for a 5.08 cm Inlet Arm Into 10.16 cm Combustion Chamber

c. The 3.81 cm Inlet Arm Into 7.62 cm Combustion Chamber

The proposed design of a 3.81 cm inlet arm entering a 7.62 cm combustion chamber was investigated to explore the creation of effective recirculation zones. Placing the inlet arm off-center, as demonstrated by Figure 11, circulated the fuel and air upon the entrance of reactants into the combustion chamber in an effort to create an initial flow direction and encourage the existence of recirculation zones. This was achieved by reducing the diameter of the inlet arm in order to direct reactant velocity, and successfully created a vortex throughout the combustion chamber.

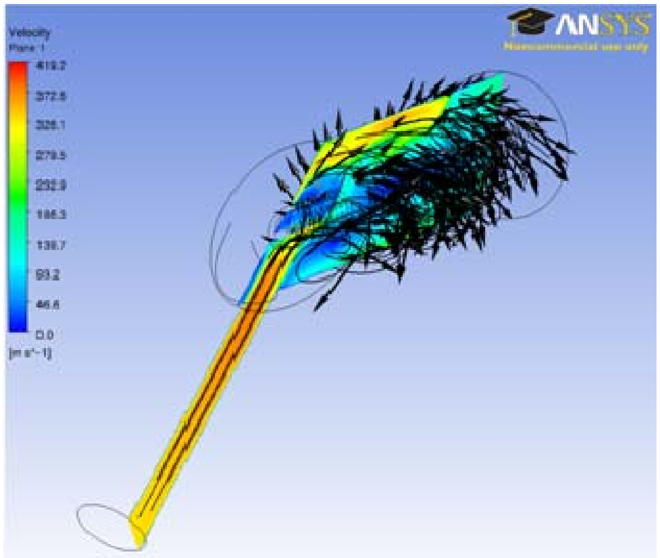

Figure 11. Fluid Flow With Velocity for a 3.81 cm Inlet Arm Into 7.62 cm Combustion Chamber, Off-Center View

The standard view of this design is provided in Figure 12 and illustrates where possible recirculation zones may exist. This design creates recirculation zones to support flame development, but simultaneously, the reduced diameter results in an increased velocity of the reactants to nearly 380 m/s, which was deemed to be too high. The protective shroud could restrict some of the velocity and result in lowered values between 25 and 42 m/s, but these continue to exceed the desired velocity offered by the four-inlet system. Regardless of the observed flow flied rotation and locally lower combustor velocities, the near sonic inflow to the combustor makes this design unfavorable.

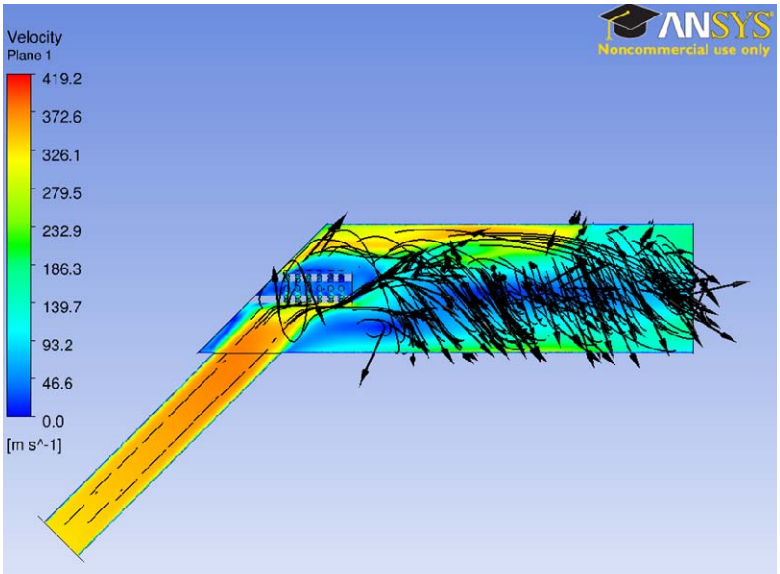

Figure 12. Fluid Flow With Velocity for a 3.81 cm Inlet Arm Into 7.62 cm Combustion Chamber, Standard View

The overall flow field structure within the combustor of this proposed design is desirable, but increased inlet arm velocity of 373 m/s also makes this design unfavorable. A modification explored altered the shroud's placement towards the position where the inlet arm intersects the combustor chamber, as illustrated in Figure 13. It was expected to remove the shroud's ability to affect the flow and interrupt the velocity of the reactants entering the combustion chamber, therefore circumventing the shroud vice traveling through the shroud. While these modifications preserved the flow circulation inside the combustion chamber, this design minimized the amount of recirculation zones due to the increased velocity throughout the combustion chamber. Moreover, the new placement did not positively affect flame development. Instead, this modification increased the velocity inside the shroud to nearly 400 m/s. It was determined that the shroud would require further protection in order to facilitate flame cultivation as well as the ability to grow in order to engulf the combustion chamber. Due to multiple reasons, this design was also abandoned.

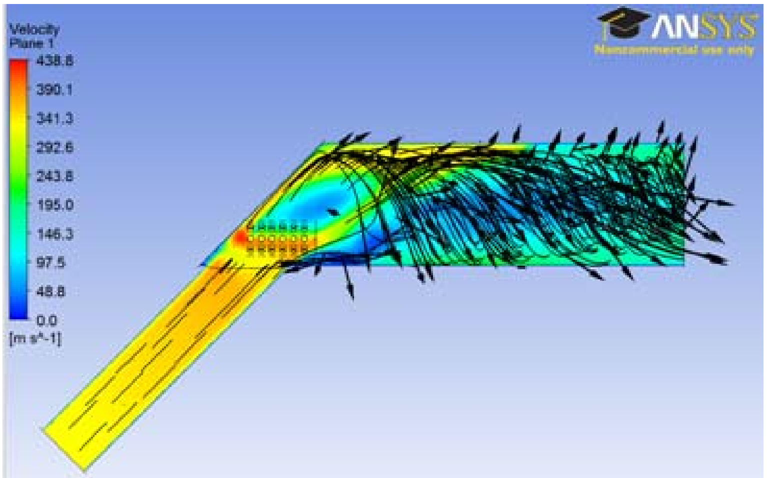

Figure 13. Fluid Flow With Velocity for a 3.81 cm Inlet Arm Into 7.62 cm Combustion Chamber, Lowered Shroud Alternation

d. The 7.62 cm Inlet Arm Into 7.62 cm Combustion Chamber

Results from the previous designs proposed demonstrated the importance of providing a manageable inlet velocity in order to support healthy flame development. Since the mass flow will remain at 0.3125 kg/s, the proposed design for a 7.62 cm inlet arm entering a 7.62 cm combustion chamber further decelerated the velocity of the reactants as they transited the inlet arm and entered the combustion chamber. CFX results in Figure 14 show reduced velocity in the inlet arm measuring 93 m/s, which then decreases further within the shroud to a velocity between 25 and 40 m/s. These lower velocities are conducive to the desired flame growth within the shroud and can be supported by the neighboring recirculation zone prior to exiting the combustion chamber. However, within the shroud, velocities were still in excess of those for the four-inlet arm design, and therefore a minor modification to the shroud porosity was required.

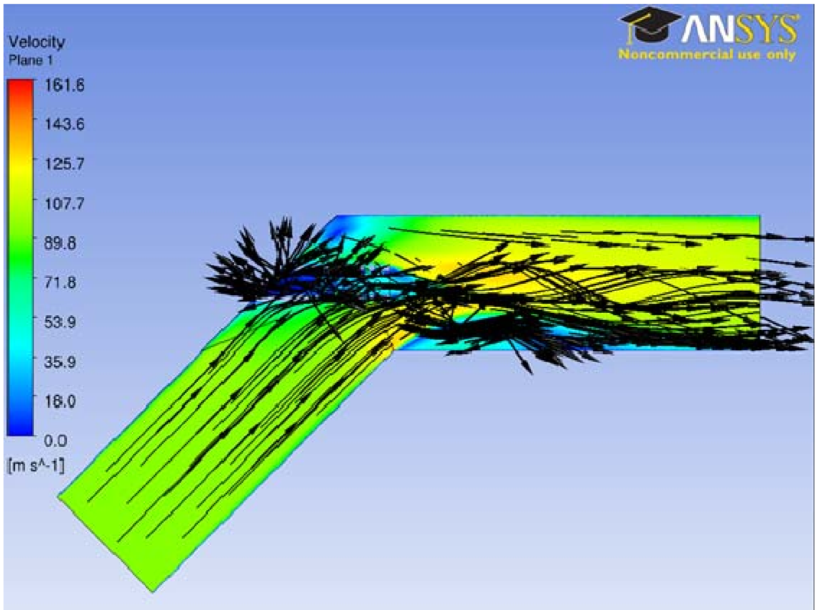

Figure 14. Fluid Flow With Velocity for a 7.62 cm Inlet Arm Into 7.62 cm Combustion Chamber

The initial design of the shroud included a geometry with 100% porosity, but the modification resulted in a 37.5 % fewer porous design, as depicted earlier in Figure 8 This decreased the velocities within the shroud to between 13 and 34 m/s, therefore producing an environment for initial flame ignition similar to the four-inlet arm design. CFX results for this modified design, in Figure 15, illustrate that the fluid flow velocity also decreased to between 15 and 35 m/s. An additional benefit was that the recirculation zones increased velocity to 18–35 m/s. Since the desired inlet arm velocities were observed in the simulations it establishes promise for this design.

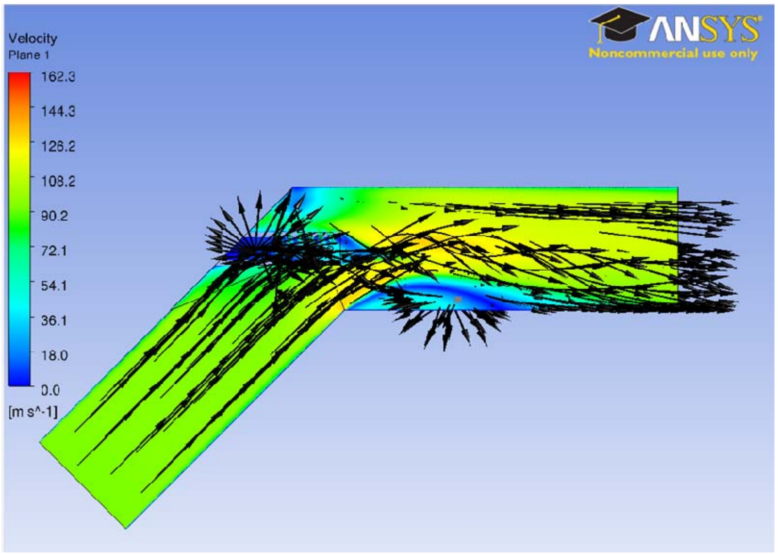

Figure 15. Fluid Flow With Velocity for a 7.62 cm Inlet Arm Into 7.62 cm Combustion Chamber, 37.5 % Fewer Holes

The design of a 7.62 cm inlet arm entering a 7.62 cm combustion chamber with a modified shroud sufficiently imitates the desired results of the four-inlet arm system. This is the analytical evidence that a successful deflagration would likely occur when using this design. A comparison of the desired results for the four-inlet arm design and this proposed single-inlet arm design is shown in Table 3.

Conditions	Four-Inlet	Single-Inlet
Inlet Velocity	~95 m/s	~93 m/s
Velocity entering combustion chamber	~105 m/s	~114 m/s
Velocity at bottom of shroud	~13 m/s	~ 14 m/s
Velocity at center of shroud	~36 m/s	~ 33 m/s
Recirculation zones	4 zones ~19–35 m/s	3 zones ~18–32 m/s

Table 3. Four-Inlet Versus Single-Inlet Cold Flow Characteristics

C. ANSYS FLUENT

FLUENT is a software package contained within ANSYS dedicated to modeling flow, turbulence, heat transfer, and chemical reactions for applications such as fluid flow over an aircraft wing, blood flow through a body, and modeling chemical reactions of mixed species (ANSYS Fluent, 2010). It was utilized for this research to map the combustion behavior of an ethylene-air mixture through both the previous four-inlet arm system and the newly designed single inlet-arm design.

1. Reacting-Flow Computational

The capability to conduct reacting-flow chemical mixture simulations for the various combustor scenarios was the primary reason for using FLUENT. However, initial use of FLUENT was limited as familiarity favored CFX. Therefore, simulations were conducted in both programs for comparison and to allow increased modeling versatility.

The first simulation conducted examined air flow through the four-inlet system. Results from CFX simulations were then compared to those of FLUENT in order to validate the initial conditions and confirm that the resulting flow fields matched, allowing for a second simulation, which included chemical reactions. Figure 16 shows the image developed in FLUENT demonstrating similar flow field characteristics as the four-inlet system in Figure 6 computed with CFX. A slight modification to elongate the combustion chamber in FLUENT was required to address a slight flow reversal error at the exit plane, but this affected neither the results of velocity nor the environment for flame development.

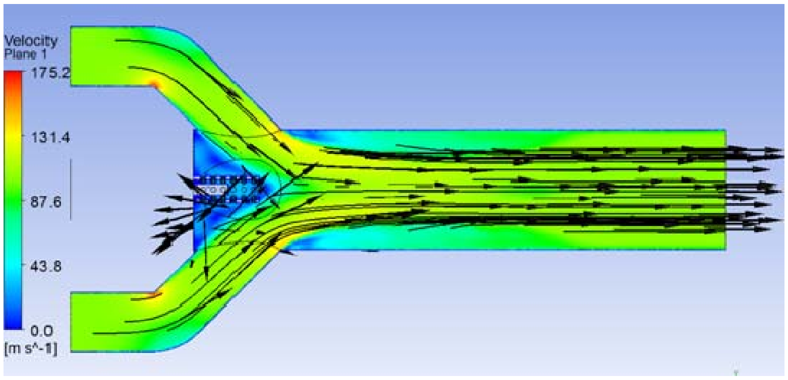

Figure 16. Fluid Flow With Velocity for Four-Inlet Arm System

2. Boundary Conditions

The computational mesh used in CFX was also utilized in the FLUENT software. The simulation setup in FLUENT represented a transient flow problem, delayed spark, and a chemical mixture suitable for combustion. The four-inlet arm design boundary conditions and computational settings are shown in Table 4.

GENERAL		Time	Transient
MODELS		Viscous	k-epsilon
k-epsilon model	Realizable	Species	Species Transport
Mixture Material	Ethylene-air	Reactions	Volumetric
SPARK		Ignition Model	Fixed Spark Size
Energy	1 J	Start time	.005 s
Shape	Cylinder	Duration	.001 s
INLET		Velocity	100 m/s
C2H4	0.065	O2	0.22
OUTLET		Gauge Pressure	0
WALL		Wall Roughness	Smooth Wall
TPI Wall		Wall Roughness	Smooth Wall
SOLUTION SETUP		Step Size	1E-6
Number of Time Steps	60000	Export File Step	5
Ma Iterations/Time Step	150	Reporting Interval	5

Table 4. Preliminary Boundary Conditions for Four-Inlet System Combustion Simulation

3. Four-Inlet Arm System

The reacting flow model failed to demonstrate successful ignition as indicated by the presence of a sufficient amount of fuel-air mixture in the combustion chamber and inside the shroud after the ignition discharge. As Figure 17 illustrates at time 0.004892s, the combustion chamber is filling with the ethylene immediately prior to initiation of the spark.

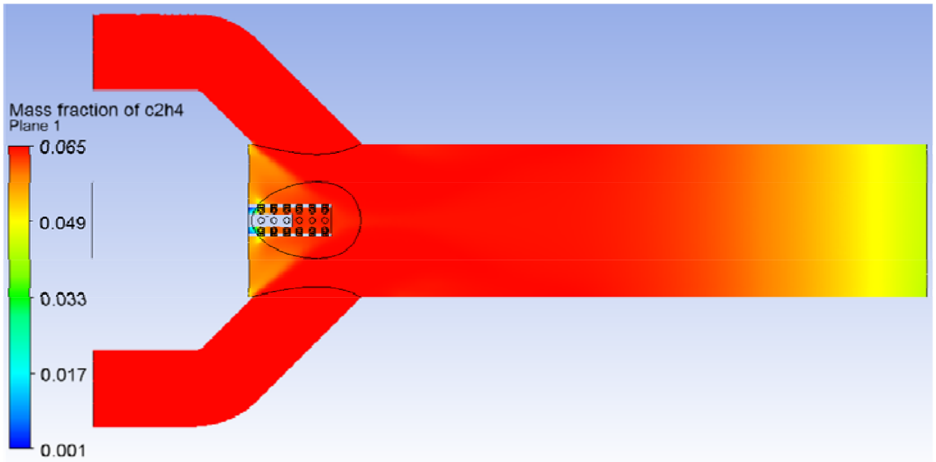

Figure 17. Four-Inlet System Filled With Ethylene

While within the combustion chamber an environment to promote flame development existed, there was no evidence of combustion. An increase in temperature at the base of ignition source demonstrates that a spark was generated, as shown in Figure 18. However, it appears that the spark was too small to ignite the mixture and may require better defining in the computational setup.

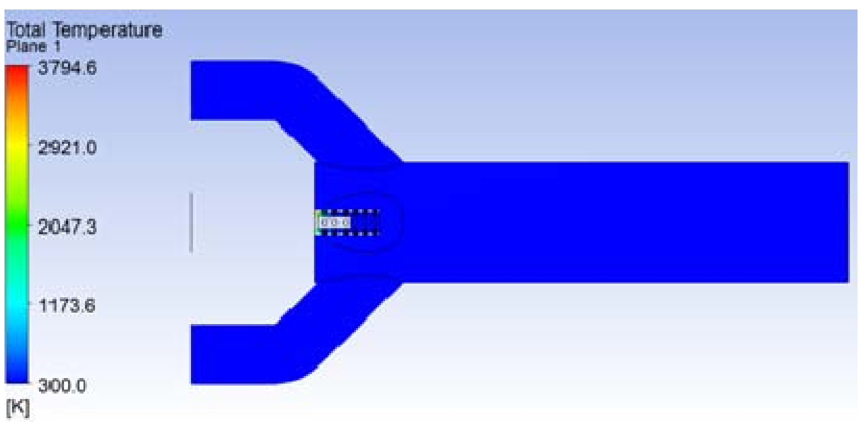

Figure 18. Four-Inlet System With Spark

At time 0.005527s, Figure 19 illustrates there was a lack of H_20, a product of combustion, and therefore it fails to confirm that combustion occurred.

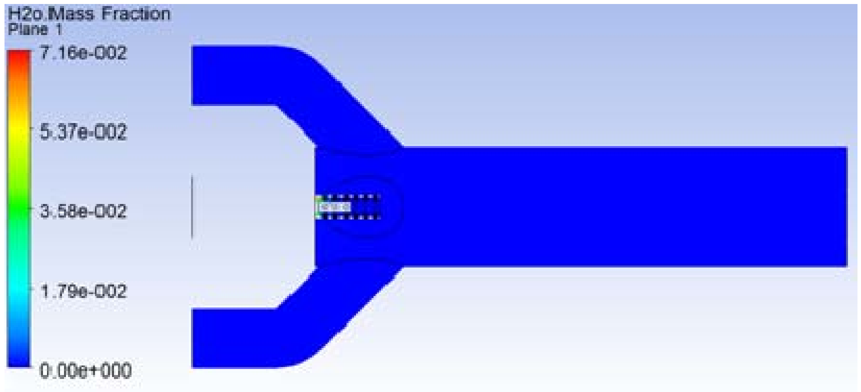

Figure 19. Four-Inlet System Containing No H_2O

Since the physical model in the four-inlet system has had successful combustion, it is assumed that boundary conditions for the computational setup are incorrect. Modeling of the spark is based on a given energy, which may have been spread out too far over a volume in the igniter.

4. Single-Inlet Arm Design

Due to the length of time needed for computation, simulations for the preferred single-inlet design were performed simultaneously with those of the four-inlet arm system. The initial boundary conditions for theses simulations are located in Appendix B. Just like the geometry of the four-inlet arm system, it was necessary to develop the flow fields to verify FLUENT results. These flows are displayed in Figure 20.

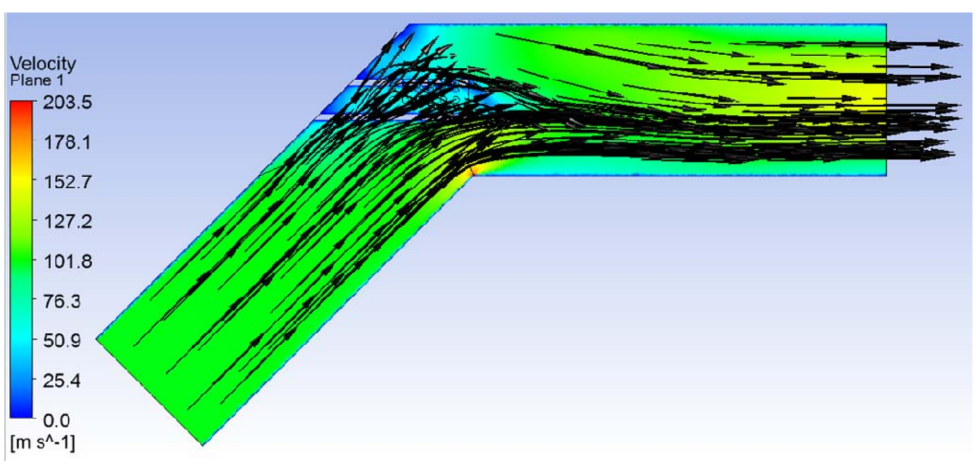

Figure 20. Fluid Flow With Velocity for Single-Inlet Arm System

The single-inlet arm design filled with ethylene at time 0.003987s is displayed in Figure 21. Once the chamber was filled, the spark was initiated and the development of products is supposed to occur.

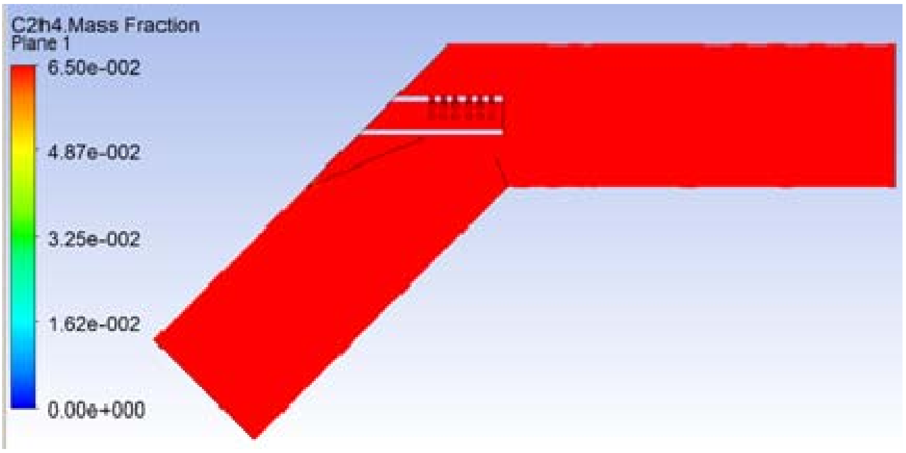

Figure 21. Single-Inlet Arm Design Filled With Ethylene

At time 0.004391s in Figure 22, shortly after the spark, there is a small amount of H_2O produced. This would normally indicate that combustion occurred, but the low magnitude of the mass fraction (6.25e-4) does not support that combustion and likely represents the small amount of water generated by the energy discharge (igniter) event.

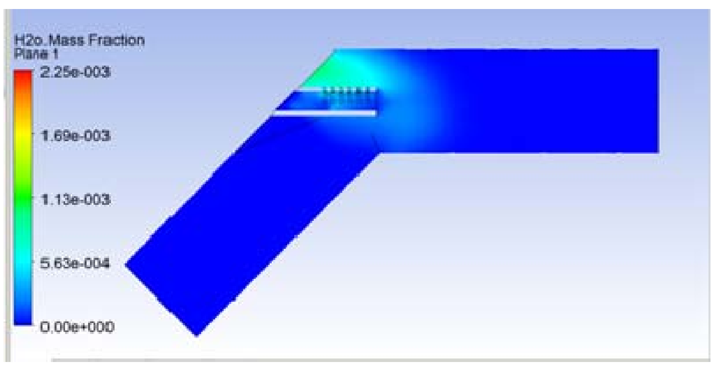

Figure 22. Single-Inlet Arm Design With H_2O Exiting Shroud

The small amount of H_2O does not reside very long above the shroud where it was expected to gain energy in the recirculation zones prior to going down the chamber. The movement of H_2O down the combustor can be seen at time step 0.005021s in Figure 23.

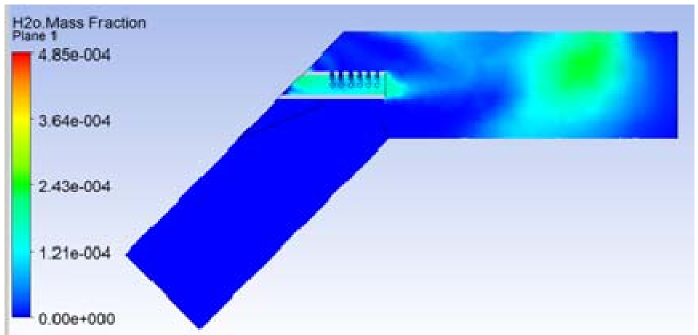

Figure 23. Single-Inlet Arm Design With H_2O Traversing the Chamber

The final time step for the simulation is at 0.006596s where the small amount of H_2O produced is exiting the combustion chamber shown in Figure 24.

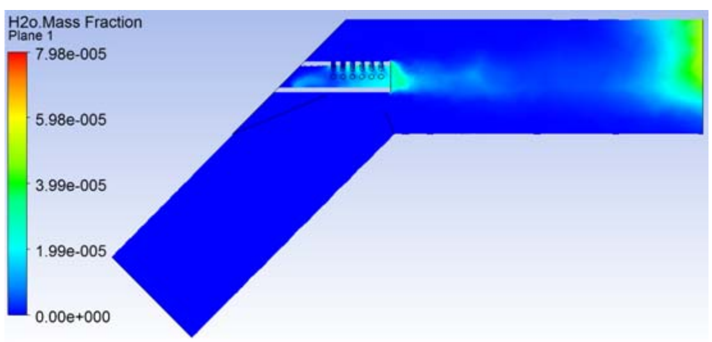

Figure 24. Single-Inlet Arm Design With H_2O Exiting Chamber

While the previous figures displayed the production of H_2O, the small amount does not support the observation that combustion really occurred. The temperature distribution in Figure 25 shows that temperature only increased roughly 250^{o}F. Had the mixture fully combusted, the temperatures should have increased to values over 2000^{o}F.

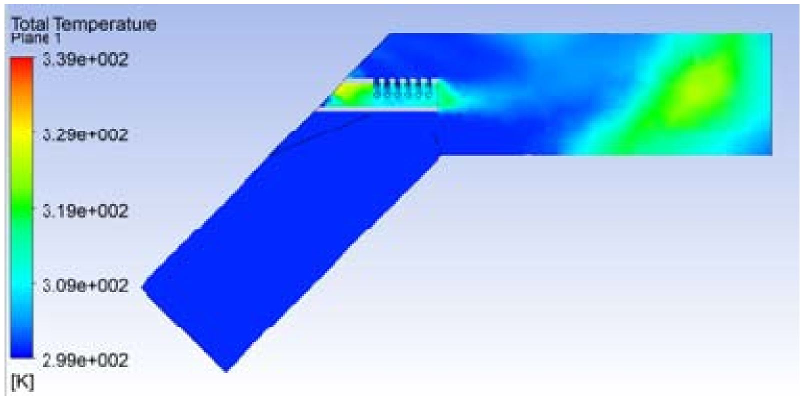

Figure 25. Single-Inlet Arm Design Temperature Displacement

The development and dispersion of H_2O shows that there was some reaction occurring in the single-inlet system; however, this could be an artifact of the ignition conditions. Since the results for the four-inlet arm are not adequate, it is not possible to determine if combustion failed due to computational setup or design. What can be gained from this simulation is the observation that there is insufficient purging of flow through the flame shroud. As the mixture burns, there is no fresh fuel-air entering the shroud, which may require further investigation of shroud design.

IV. FINAL DESIGN DECISION

Models evaluated using CFX and FLUENT revealed that the 7.62 cm single inlet arm into 7.62 cm combustion chamber design would likely produce adequate velocities and flame development. Based on this analysis, physical pieces were commissioned, according to compatibility measurements, and placed on the test platform.

A. SOLIDWORKS DESIGN

Building the single-inlet design involved two considerations: consistency with simulations and modularity. Retaining the geometries used during CFD and FLUENT simulations maintain consistency. Establishing modularity allows minor alterations during system testing, simultaneously providing opportunities for improving the single-inlet arm design.

The first concern was the proper insulation of the TPI cathode, which required a Teflon sleeve to isolate the cable and plug. The 45^{o} casing contained channels to provide a cooling ability for the system during long duration runs. Modularity was also taken into account when building the 45^{o} insert that maintained position of the shroud and igniter. If further testing desired a different location for the shroud or igniter, the insert could be replaced. An exploded view of the single-inlet arm design assembly is depicted in Figure 26.

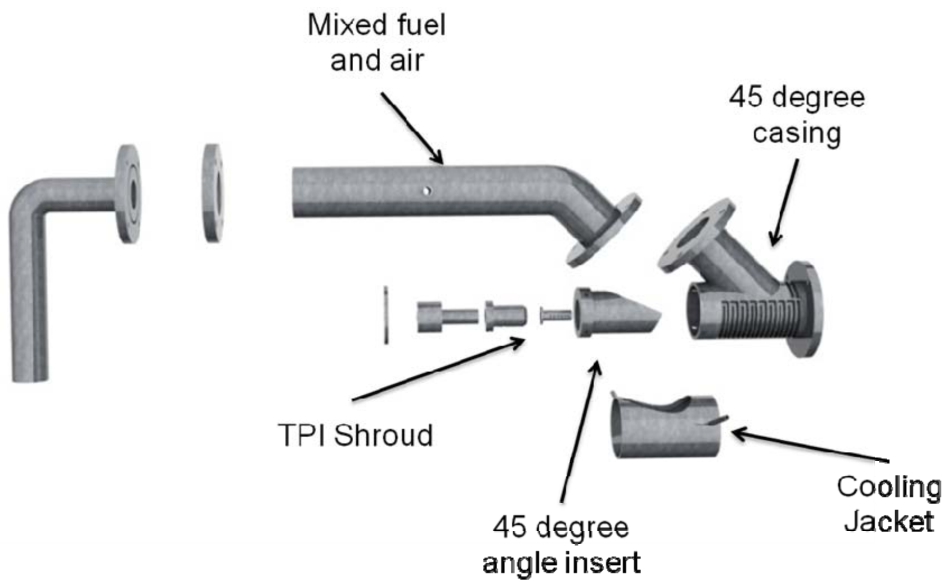

Figure 26. Exploded View of the Single-Inlet Arm Design Assembly

Detailed drawings provided to the machinist for fabrication are located in Appendix C. Many of the pieces fit inside of each other, requiring tolerances within a thousand of an inch to be assigned to the majority of the pieces. A cutaway illustration in Figure 27 shows the assembled unit and justification for such tight tolerances.

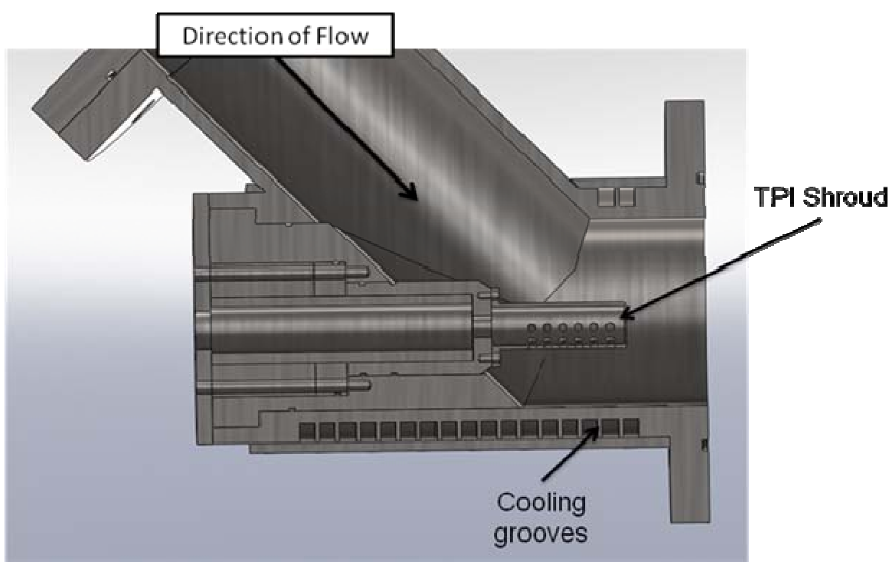

Figure 27. Cutaway Illustration of the Single-Inlet Arm Design

B. FABRICATED HARDWARE

Selections of the fabricated combustor components are pictured in Figure 28. This completed adapter piece and fuel-mixing inlet tube attach to the primary combustor.

Figure 28. Adapter and Fuel-Mixing Inlet Arm

The hardware depicted in Figure 29 shows the outer casing before and after the water jacket casing is applied as well as the 45^{o} section. The channeled grooves will utilize cooling water for the combustor.

Figure 29. The 45^{o} Outer Casing

The plate used to hold the pieces in place and the 45^{o} insert are in Figure 30 without the angle cut.

Figure 30. Cap and 45° Insert

The shroud and TPI/Gas Turbine plug incasing are shown in Figure 31. However, the holes have not been cut into the shroud. The Teflon tube is for insulating the plug and cable.

Figure 31. Shroud and Teflon Tube

The completed system from the machines is shown in Figure 32. They are to be assembled, incorporated to the PDE, and tested at a variety of frequencies, pressures, and fuel mixtures.

Figure 32. Completed Machined Hardware

VI. SUMMARY AND CONCLUSION

The four-inlet combustor design successfully created combustion for the PDC. However, streamlining this system was needed to allow practical applicability by reducing the number of inlet arms. The single-inlet combustor design was determined using previous research and modeling programs to reproduce favorable flow flied characteristics of the four-inlet combustor system.

CFD simulation programs, such as CFX and FLUENT, examined the flow fields and resulting velocities inside the combustion chamber for four proposed designs. The FLUENT software package also attempted to investigate the ignition and combustion behavior as well. Although combustion was not observed, it was not determined if that was due to failure to define proper computational boundary conditions or the design itself. The use of FLUENT is a still an acceptable method of modeling combustion, but will require more work in understanding the software modeling program with larger geometries.

It was determined from the results that were available that a geometry with a single-inlet arm design utilizing a 7.62 cm inlet entering a 7.62 cm combustion chamber at a 45^{o} dump angle should produce an acceptable flow field. Hardware was fabricated for testing at the Rocket Propulsion Laboratory at the Naval Postgraduate School.

Upon arrival and assembly of the fabricated hardware, experimental testing of the preferred design will establish a path for future research. The follow-on research will explore the operational limits of this single-inlet arm PDC through manipulation of boundary conditions such as different pressures, fuels, frequencies, TPI positions, and shroud usage. Moreover, this design’s modularity invites future improvements and applicability to contribute to the evolution of PDCs.

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APPENDIX A. MESHING AND CFX SETUP

A. THE 5.08 CM INLET ARM INTO 7.62 CM COMBUSTOR

Meshing Conditions			
Max Body Spacing	0.001 mm	Angular Resolution	30^o
Min Edge Length	0.0001 mm	Max Edge Length	0.001 mm
Inflation Layers	20	Expansion Factor	1.2
Min Internal Angle	5^o	TPI Inflation Max Thick	0.003 mm
Max External Angle	15^o	Nodes	1858688
Pyramids	2689	Prisms	885897
Tetrahedra	10324274	Total Elements	10415560
Boundary Conditions			
INLET		Mass Flow Rate	0.3125 kg/s
Flow Regime	Subsonic	Static Temperature	480 K
OUTLET		Mass Flow Rate	0.3125 kg/s
WALL		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
TPI Wall		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
INITIALIZATION		Pressure	1 atm
Material	Air Ideal Gas	Heat Transfer	Total Energy
Turbulence	k-Epsilon	Velocity u/v/w	0/0/60 m/s
Temperature	400 K	Intensity	Medium

B. THE 5.08 CM INLET ARM INTO 10.16 CM COMBUSTOR

Meshing Conditions			
Max Body Spacing	0.0015 mm	Angular Resolution	30^{o}
Min Edge Length	0.0001 mm	Max Edge Length	0.0015 mm
Inflation Layers	5	Expansion Factor	1.2
Min Internal Angle	2.5^{o}	TPI Inflation Max Thick	0.003 mm
Max External Angle	10^{o}	Nodes	911279
Pyramids	2540	Prisms	59651
Tetrahedra	4495877	Total Elements	5058068
Boundary Conditions			
INLET		Mass Flow Rate	0.3125 kg/s
Flow Regime	Subsonic	Static Temperature	480 K
OUTLET		Mass Flow Rate	0.3125 kg/s
WALL		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
TPI Wall		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
INITIALIZATION		Pressure	1 atm
Material	Air Ideal Gas	Heat Transfer	Total Energy
Turbulence	k-Epsilon	Velocity u/v/w	0/0/60 m/s
Temperature	400 K	Intensity	Medium

C. THE 3.81 CM INLET ARM INTO 7.62 CM COMBUSTOR

Meshing Conditions			
Max Body Spacing	0.00115 mm	Angular Resolution	30^{o}
Min Edge Length	0.000115 mm	Max Edge Length	0.00115 mm
Inflation Layers	20	Expansion Factor	1.1
Min Internal Angle	5	TPI Inflation Max Thick	0.003 mm
Max External Angle	15	Nodes	1501168
Pyramids	3325	Prisms	235096
Tetrahedra	7859408	Total Elements	8097829
Boundary Conditions			
INLET		Mass Flow Rate	0.3125 kg/s
Flow Regime	Subsonic	Static Temperature	480 K
OUTLET		Mass Flow Rate	0.3125 kg/s
WALL		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
TPI Wall		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
INITIALIZATION		Pressure	1 atm
Material	Air Ideal Gas	Heat Transfer	Total Energy
Turbulence	k-Epsilon	Velocity u/v/w	0/0/60 m/s
Temperature	400 K	Intensity	Medium

D. THE 7.62 CM INLET ARM INTO 7.62 CM COMBUSTOR

Meshing Conditions			
Max Body Spacing	0.0011 mm	Angular Resolution	30^{o}
Min Edge Length	0.0001 mm	Max Edge Length	0.0011 mm
Inflation Layers	5	Expansion Factor	1.2
Min Internal Angle	5^{o}	TPI Inflation Max Thick	0.003 mm
Max External Angle	15^{o}	Nodes	1981635
Pyramids	2574	Prisms	80512
Tetrahedra	11077246	Total Elements	11160332
Boundary Conditions			
INLET		Mass Flow Rate	0.3125 kg/s
Flow Regime	Subsonic	Static Temperature	480 K
OUTLET		Mass Flow Rate	0.3125 kg/s
WALL		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
TPI Wall		Wall Roughness	Smooth Wall
Mass and Momentum	No Slip Wall	Heat Transfer	Adiabatic
INITIALIZATION		Pressure	1 atm
Material	Air Ideal Gas	Heat Transfer	Total Energy
Turbulence	k-Epsilon	Velocity u/v/w	0/0/60 m/s
Temperature	400 K	Intensity	Medium

APPENDIX B. FLUENT SETUP FOR SINGLE ARM INLET

Boundary Conditions			
GENERAL		Time	Transient
MODELS		Viscous	k-epsilon
k-epsilon model	Realizable	Species	Species Transport
Mixture Material	Ethylene-air	Reactions	Volumetric
SPARK		Ignition Model	Fixed Spark Size
Energy	1 J	Start time	.004 s
Shape	Cylinder	Duration	.001 s
INLET		Velocity	100 m/s
C2H4	0.065	O2	0.22
OUTLET		Gauge Pressure	0
WALL		Wall Roughness	Smooth Wall
TPI Wall		Wall Roughness	Smooth Wall
SOLUTION SETUP		Step Size	1E-6
Number of Time Steps	60000	Export File Step	5
Ma Iterations/Time Step	150	Reporting Interval	5

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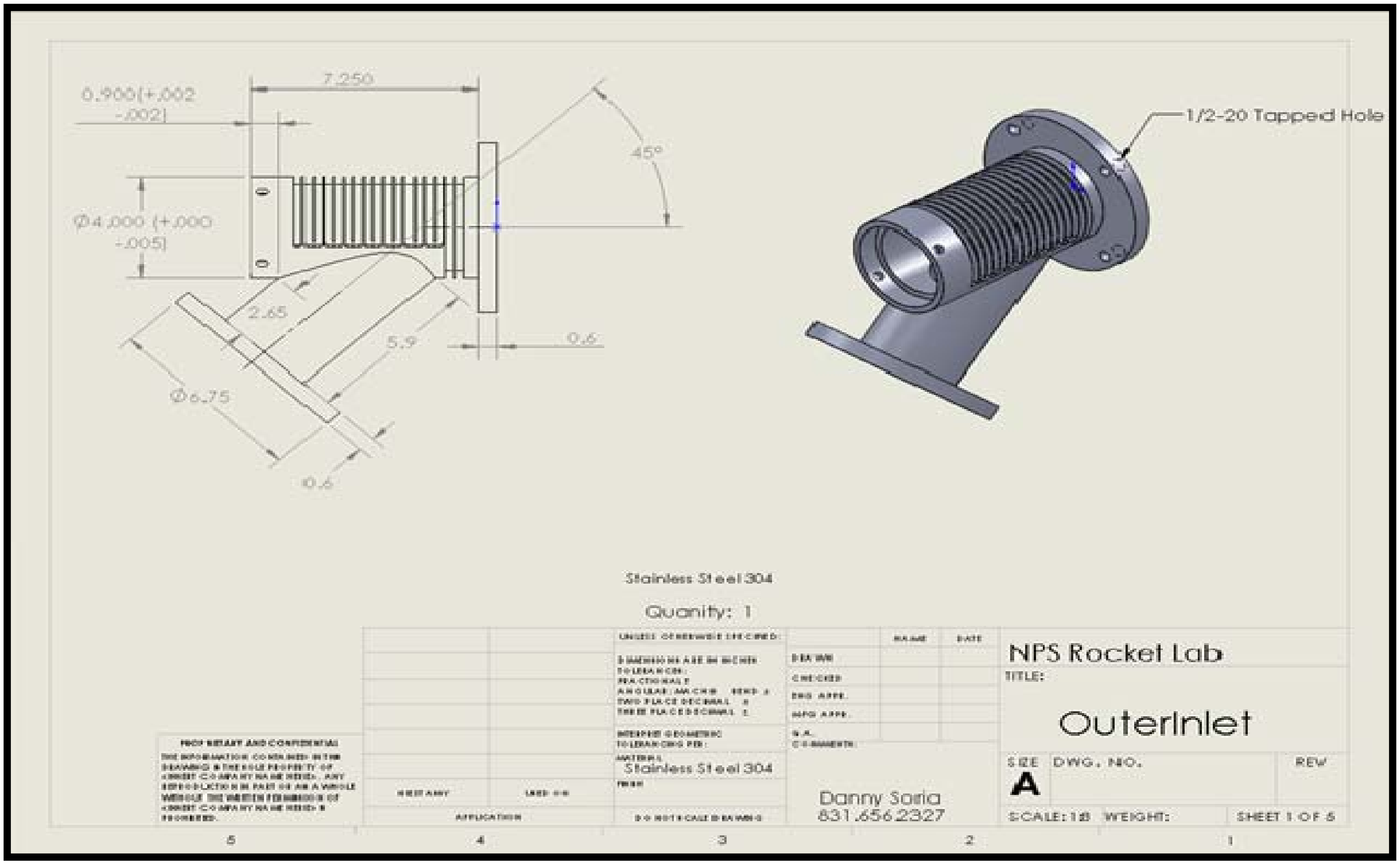
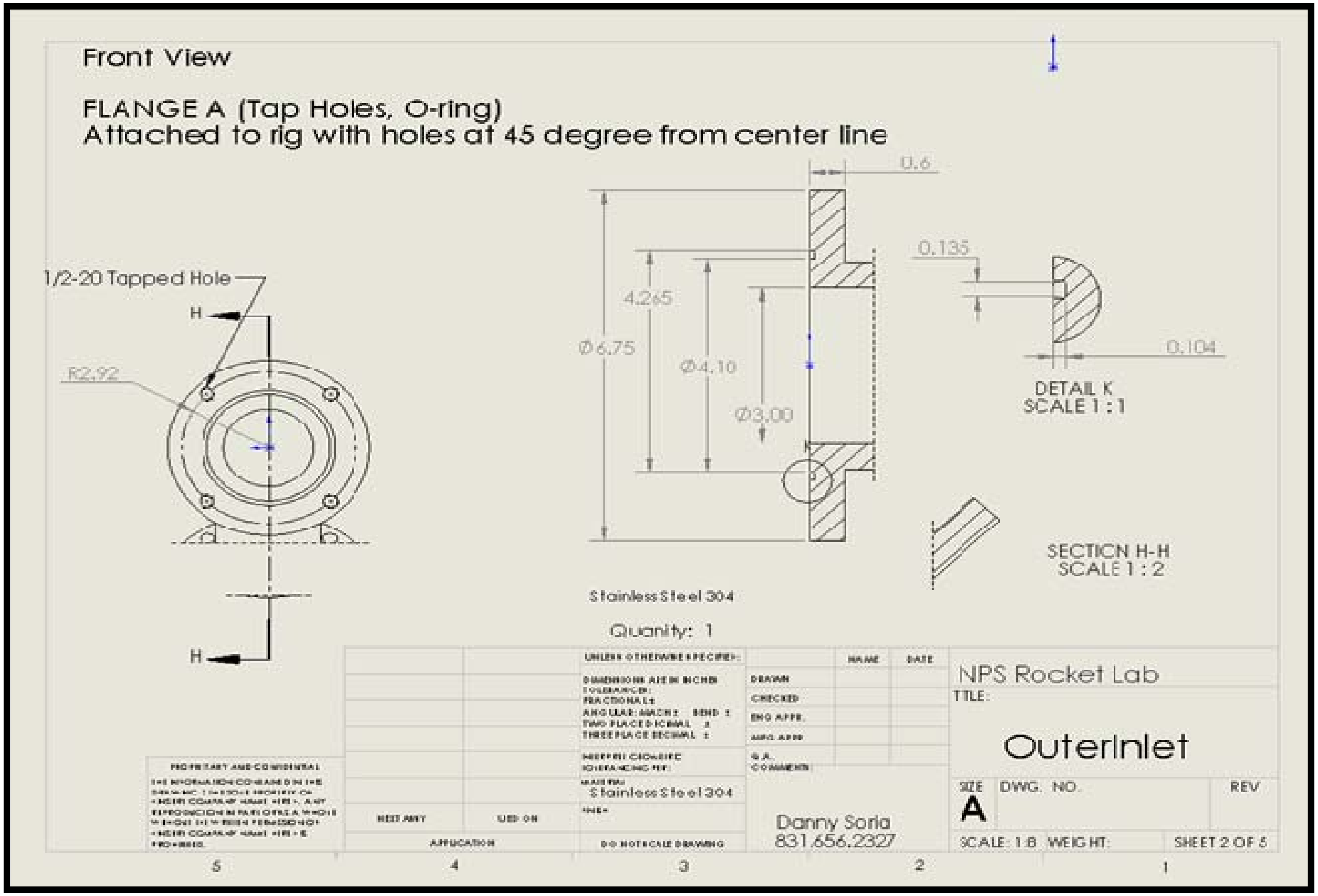
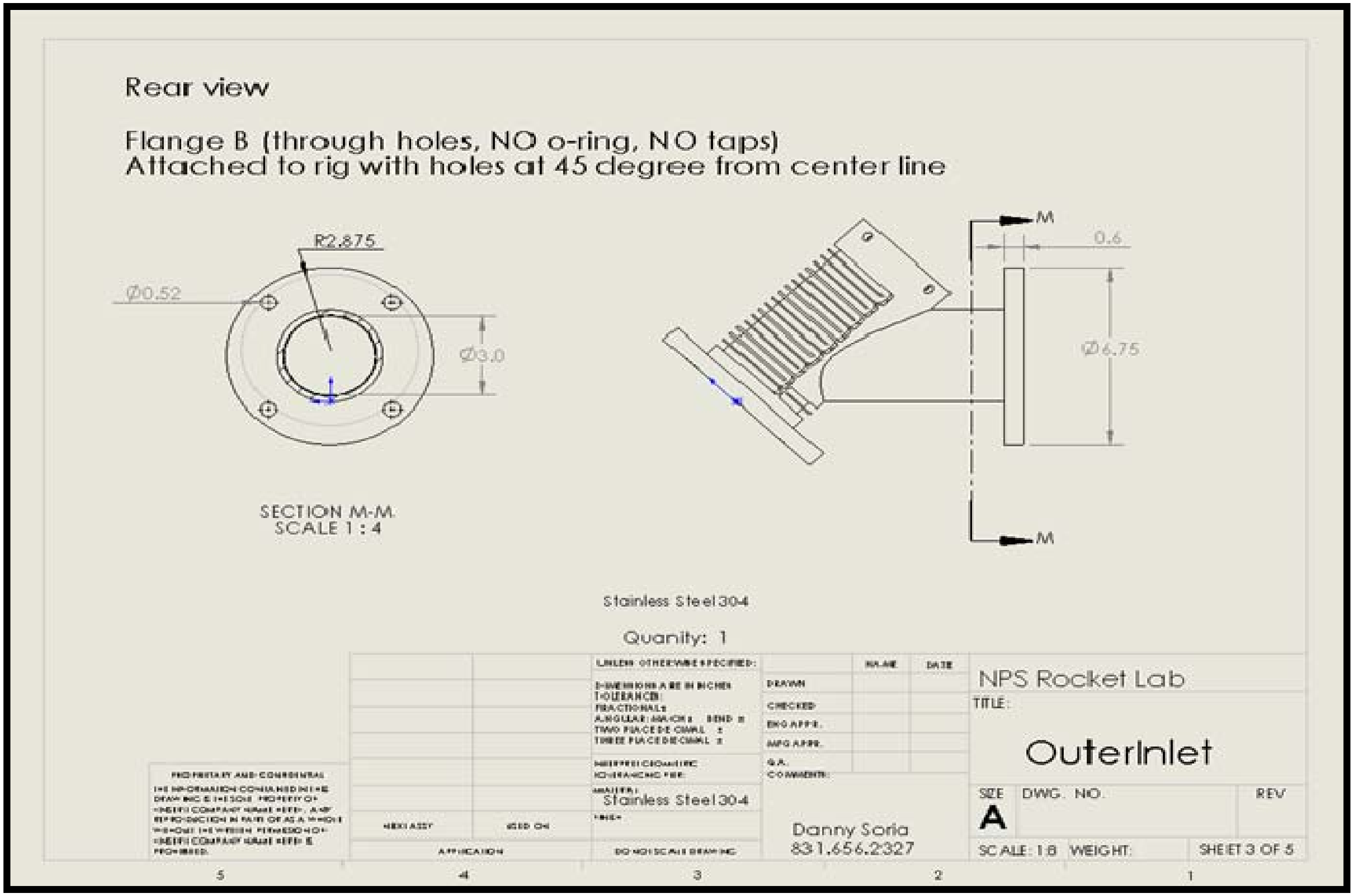
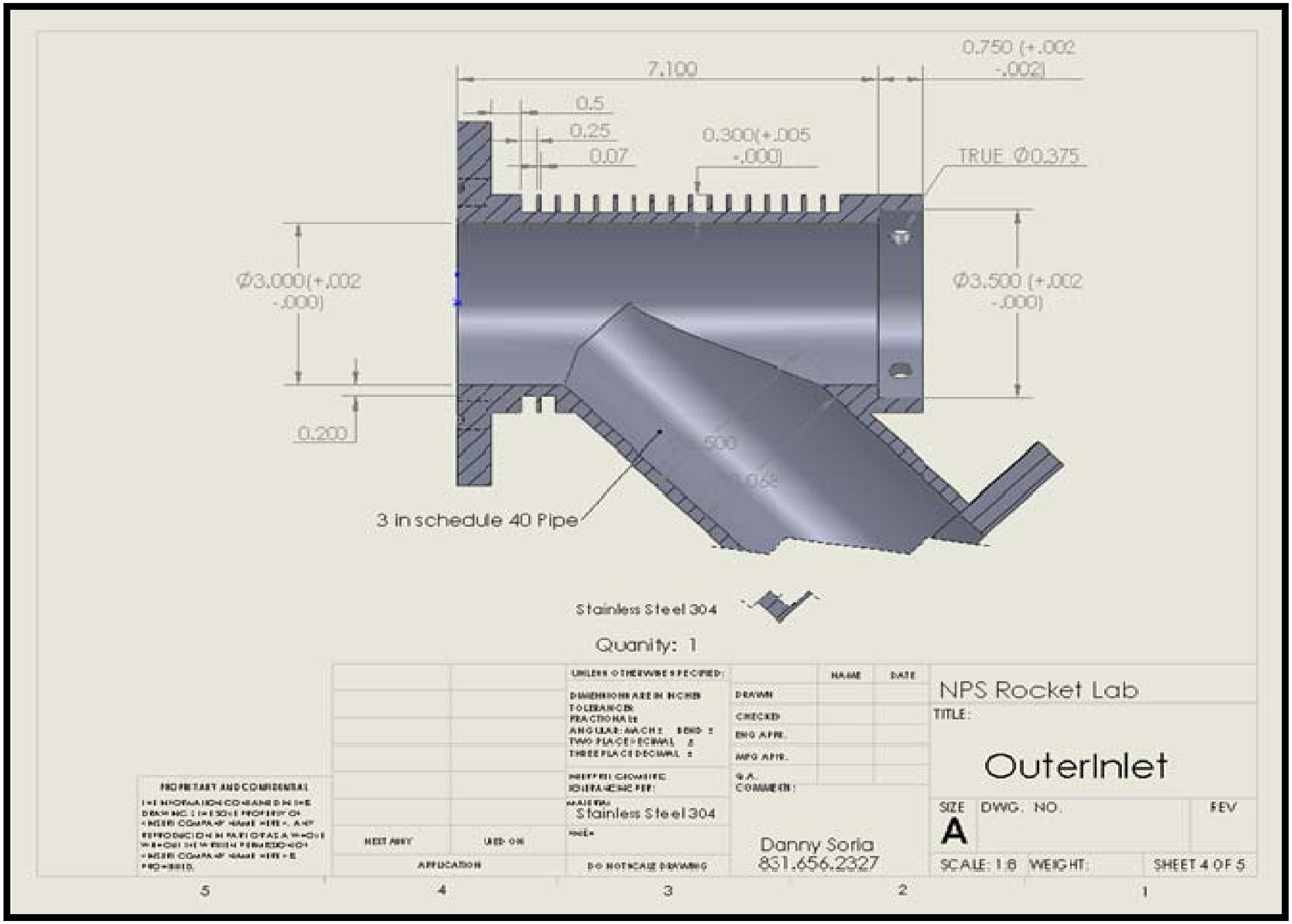
APPENDIX C. FINAL DESIGN PLANS

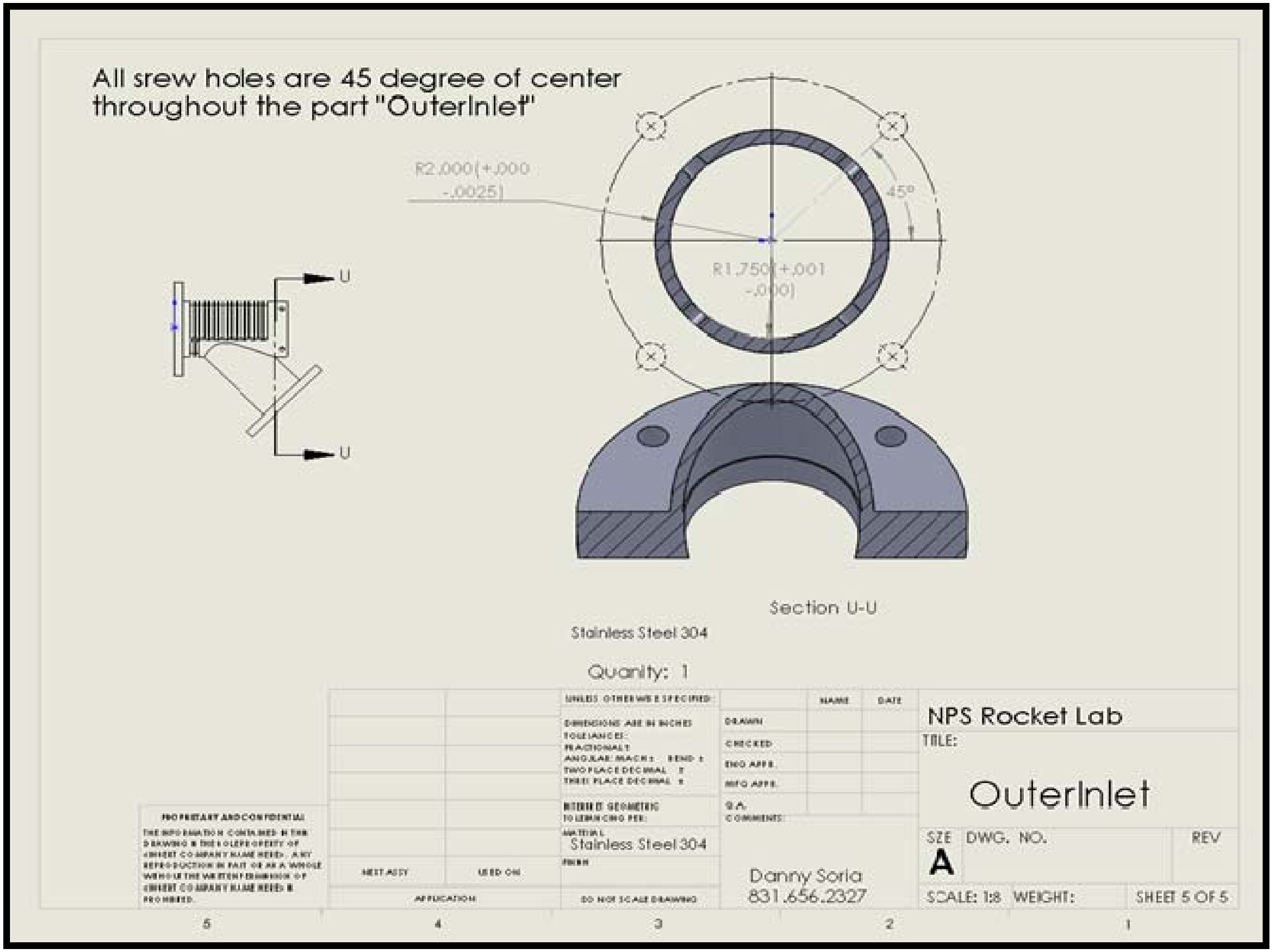
A. ENCASING OF INLET




Front View
FLANGE A (Tap Holes, O-ring)
Attached to rig with holes at 45 degree from center line
1/2-20 Tapped Hole
H
R2.92
0.6
4.265
Ø6.75
Ø4.10
Ø3.00
0.135
0.104
DETAIL K
SCALE 1 : 1
SECTION H-H
SCALE 1 : 2
Stainless Steel 304
Quanity: 1
NPS Rocket Lab
TITLE:
OuterInlet
SIZE
A
DWG. NO.
REV
SCALE: 1:8
WEIGHT:
SHEET 2 OF 5
Danny Soria
831.656.2327
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
Stainless Steel 304
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
5
4
3
2
1

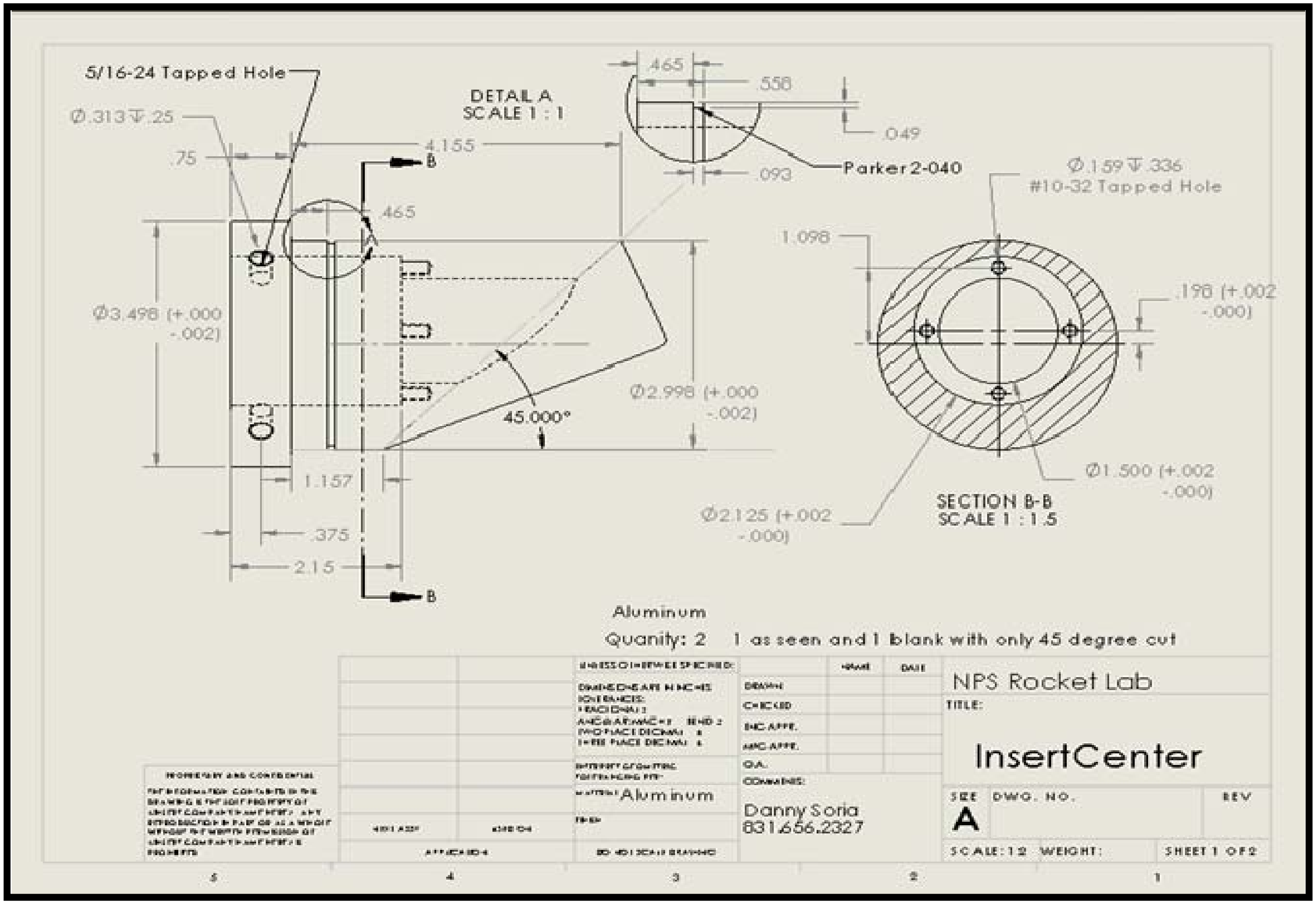

Rear view
Flange B (through holes, NO o-ring, NO taps)
Attached to rig with holes at 45 degree from center line
R2.875
Ø0.52
Ø3.0
SECTION M-M
SCALE 1 : 4
M
0.6
Ø6.75
M
Stainless Steel304
Quanity: 1
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Stainless Steel304
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
Danny Soria
831.656.2327
NPS Rocket Lab
TITLE:
OuterInlet
SIZE
A
DWG. NO.
REV
SCALE: 1:8
WEIGHT:
SHEET 3 OF 5
5
4
3
2
1

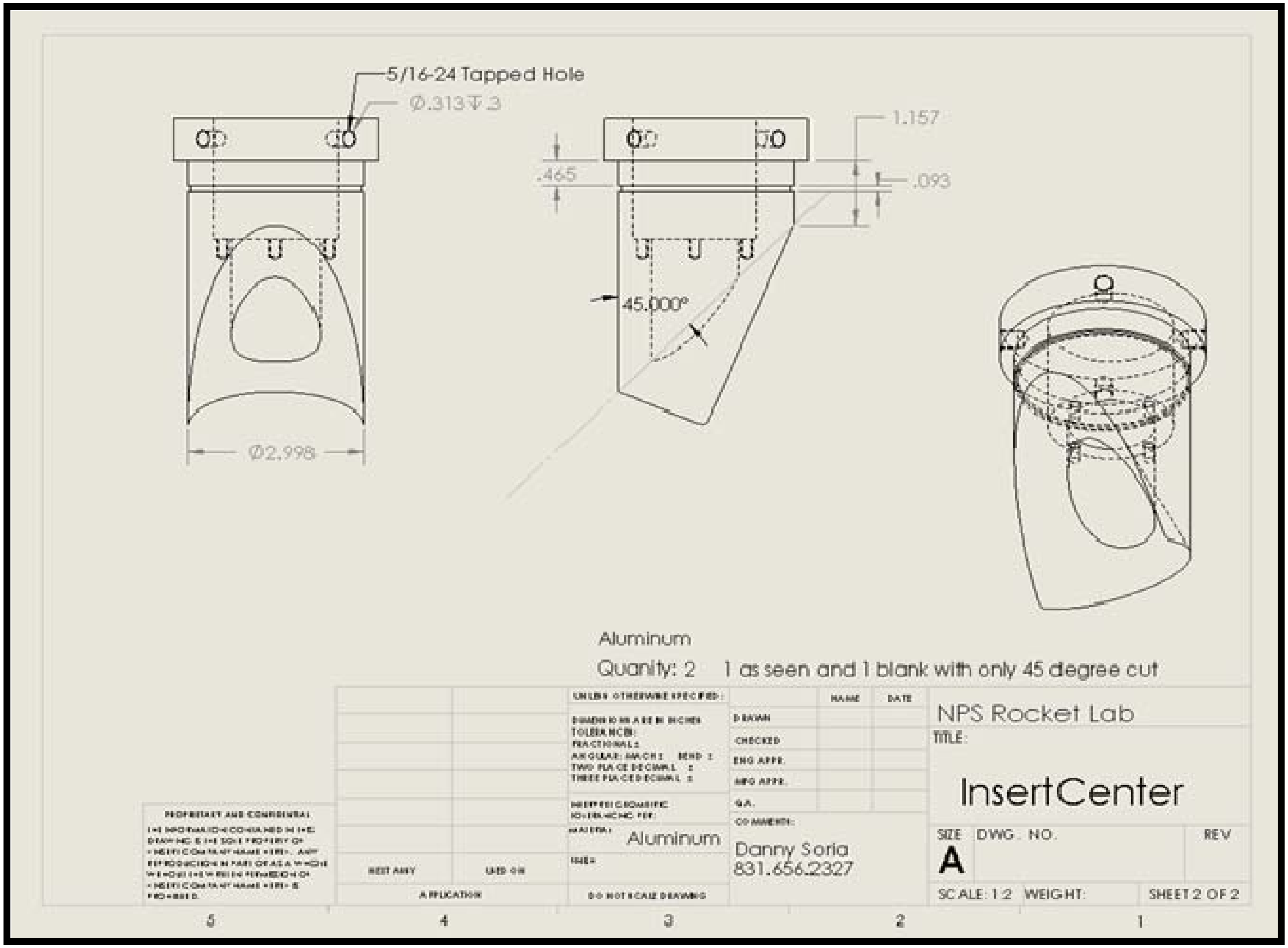

7.100
0.750 (+.002 -.002)
0.5
0.25
0.07
0.300(+.005 -.000)
TRUE Ø0.375
Ø3.000(+.002 -.000)
Ø3.500 (+.002 -.000)
0.200
3 in schedule 40 Pipe
Stainless Steel 304
Quanity: 1
NPS Rocket Lab
TITLE:
OuterInlet
SIZE
A
DWG. NO.
REV
SCALE: 1:8
WEIGHT:
SHEET 4 OF 5
Danny Soria
831.656.2327
Stainless Steel 304
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
DRAWN
CHECKED
NAME
DATE
5
4
3
2
1



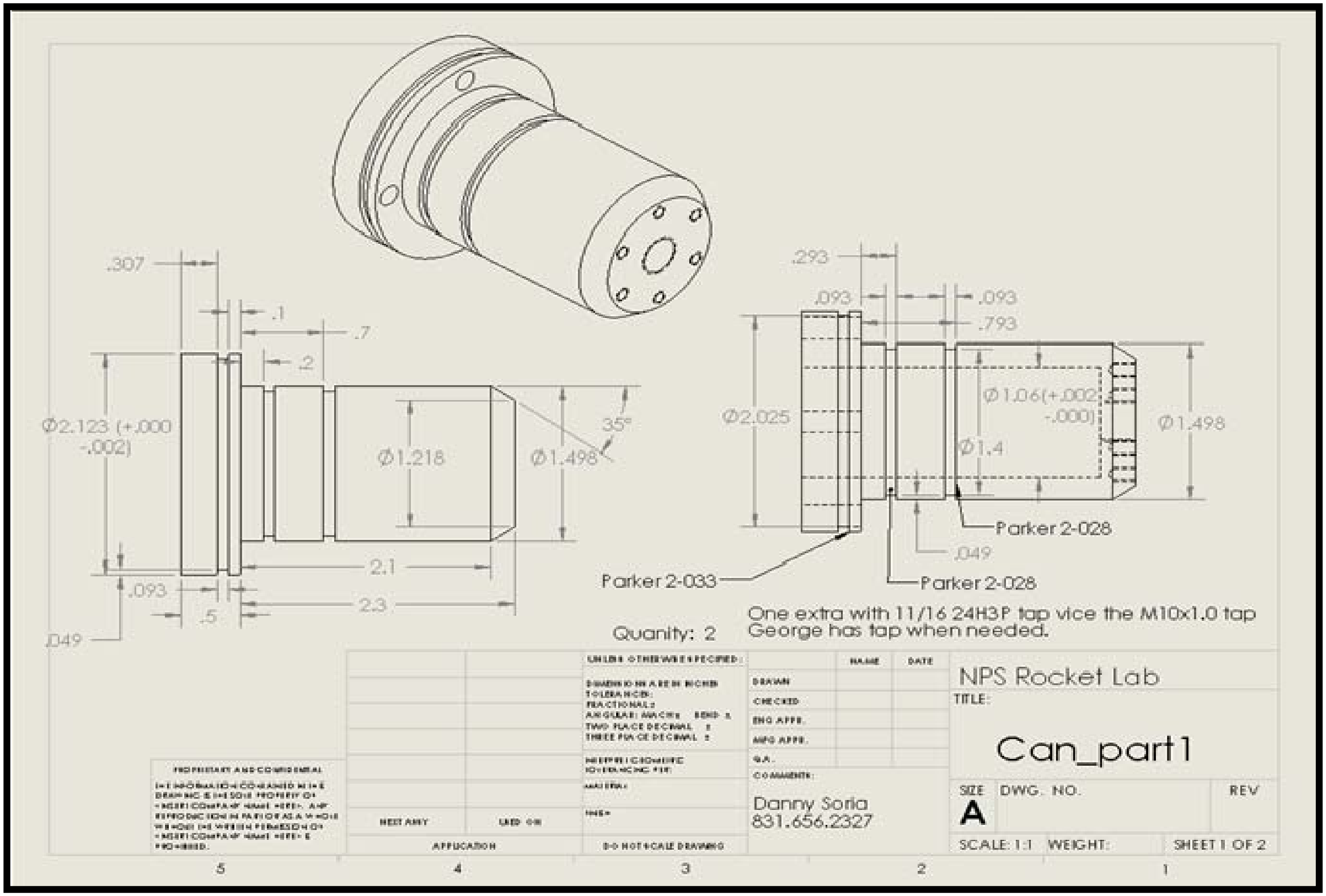
All srew holes are 45 degree of center
throughout the part "OuterInlet"
R2.000(+.000
-.0025)
45°
R1.750(+.001
-.000)
U
U
Section U-U
Stainless Steel 304
Quanity: 1
NPS Rocket Lab
TITLE:
OuterInlet
SIZE
A
DWG. NO.
REV
SCALE: 1:8
WEIGHT:
SHEET 5 OF 5
Danny Soria
831.656.2327
MATERIAL
Stainless Steel 304

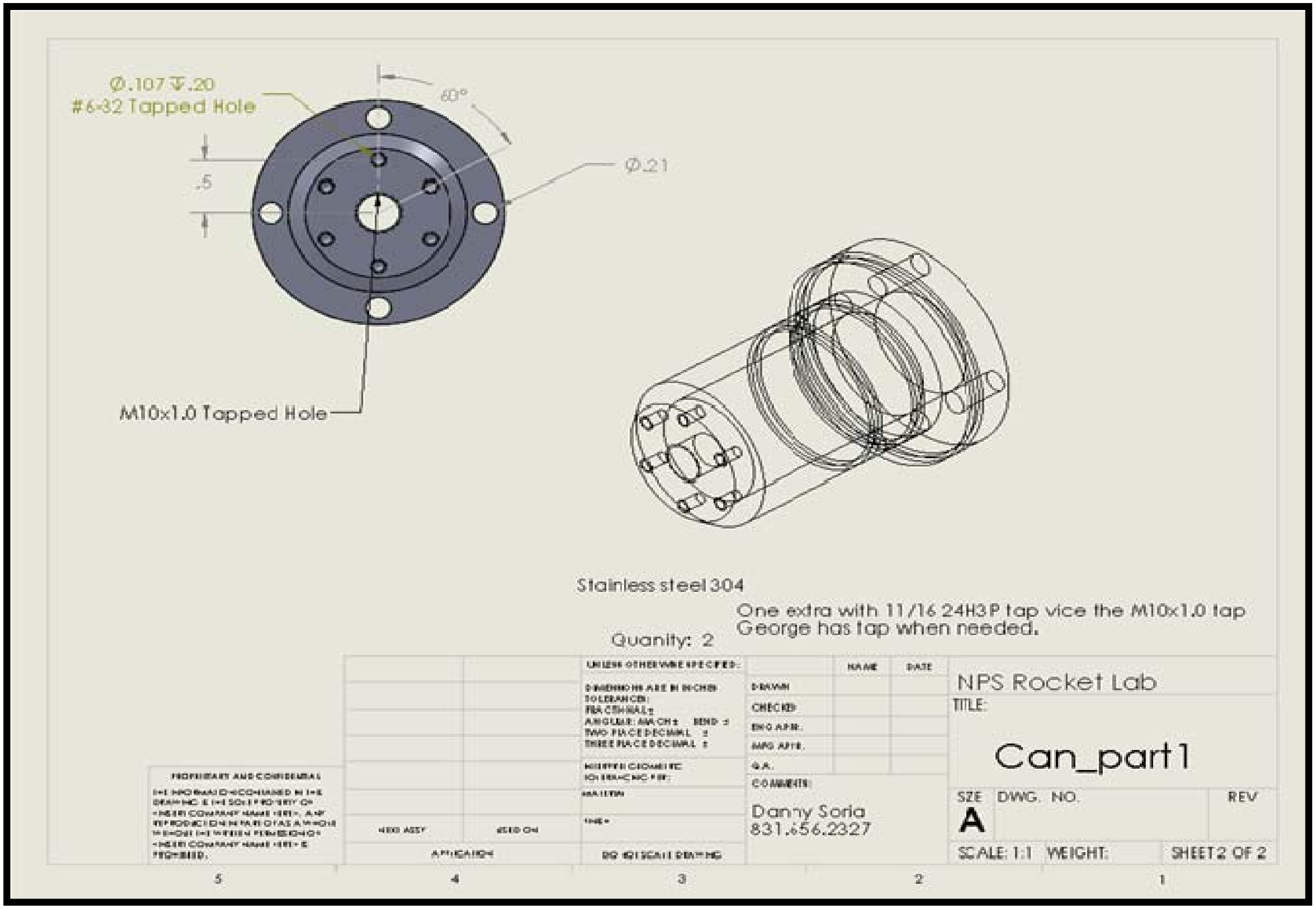
B. CENTER INSERT



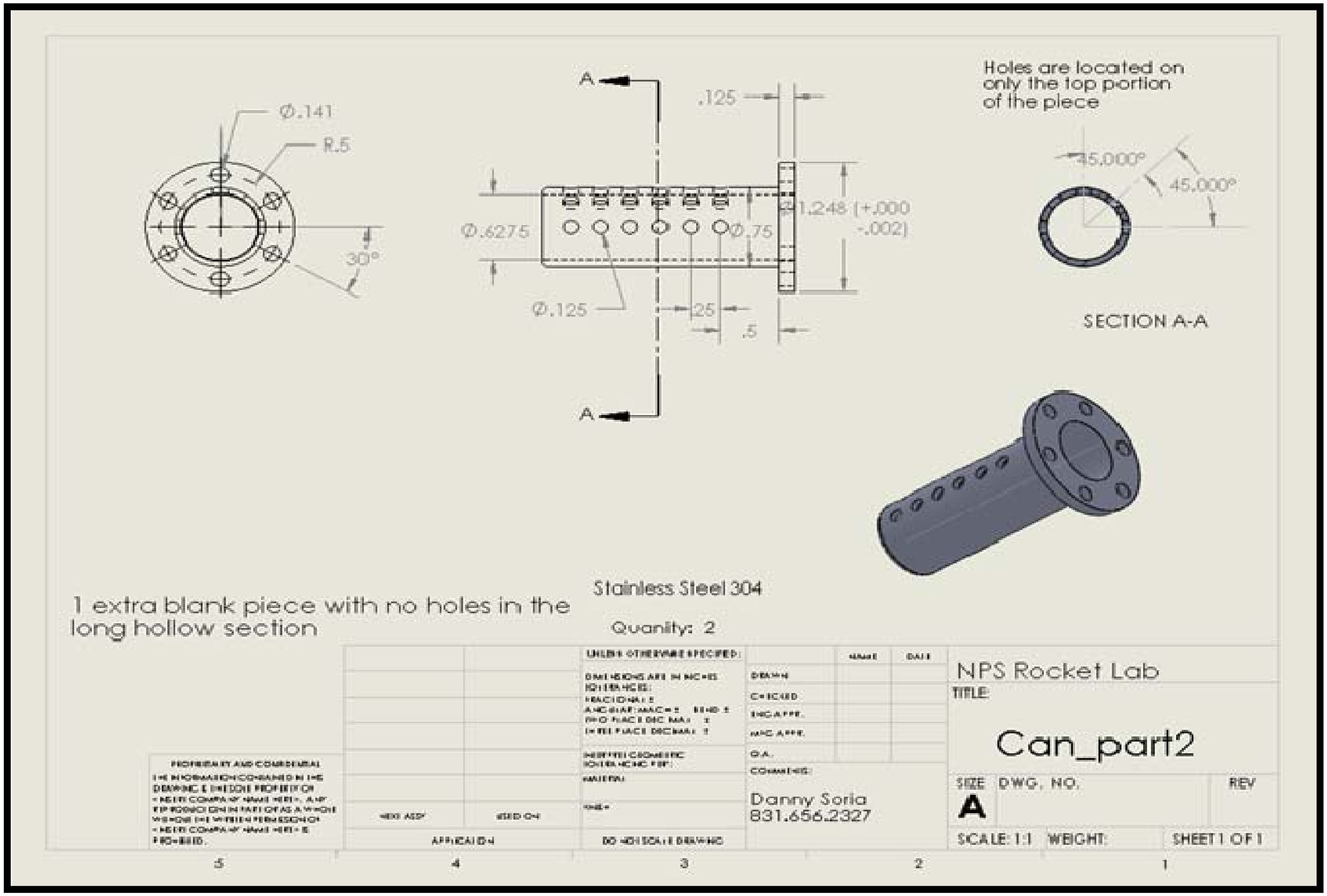

5/16-24 Tapped Hole
Ø.313⊽.3
1.157
.465
.093
45.000°
Ø2.998
Aluminum
Quanity: 2 1 as seen and 1 blank with only 45 degree cut
NPS Rocket Lab
TITLE:
InsertCenter
MATERIAL
Aluminum
Danny Soria
831.656.2327
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 2 OF 2
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
5
4
3
2
1

C. SHROUD BASE

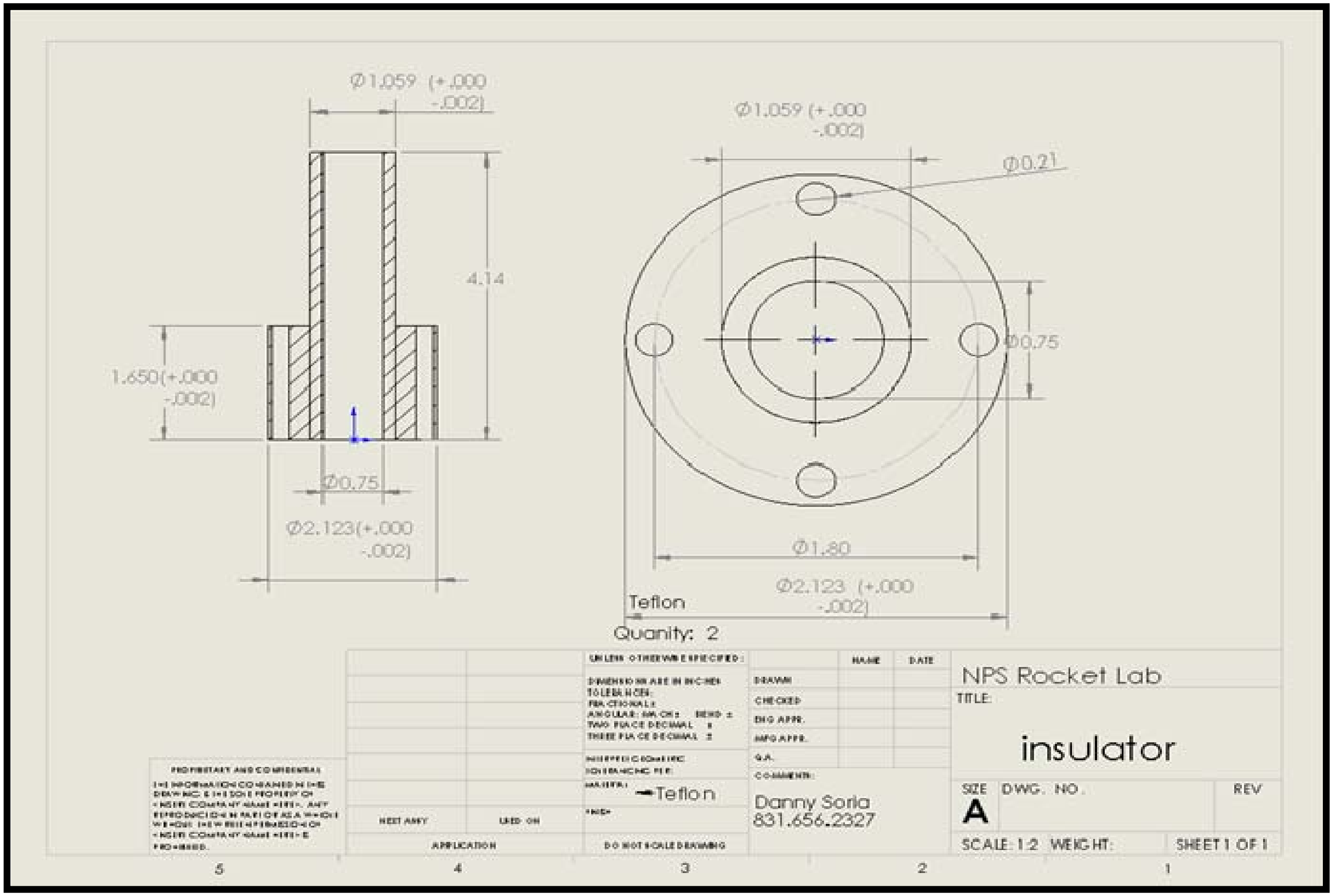



Ø.107 ↧.20
#6-32 Tapped Hole
60°
.5
Ø.21
M10x1.0 Tapped Hole
Stainless steel 304
One extra with 11/16 24H3P tap vice the M10x1.0 tap
George has tap when needed.
Quanity: 2
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Danny Soria
831.656.2327
NPS Rocket Lab
TITLE:
Can_part1
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 2 OF 2
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
5
4
3
2
1

D. SHROUD

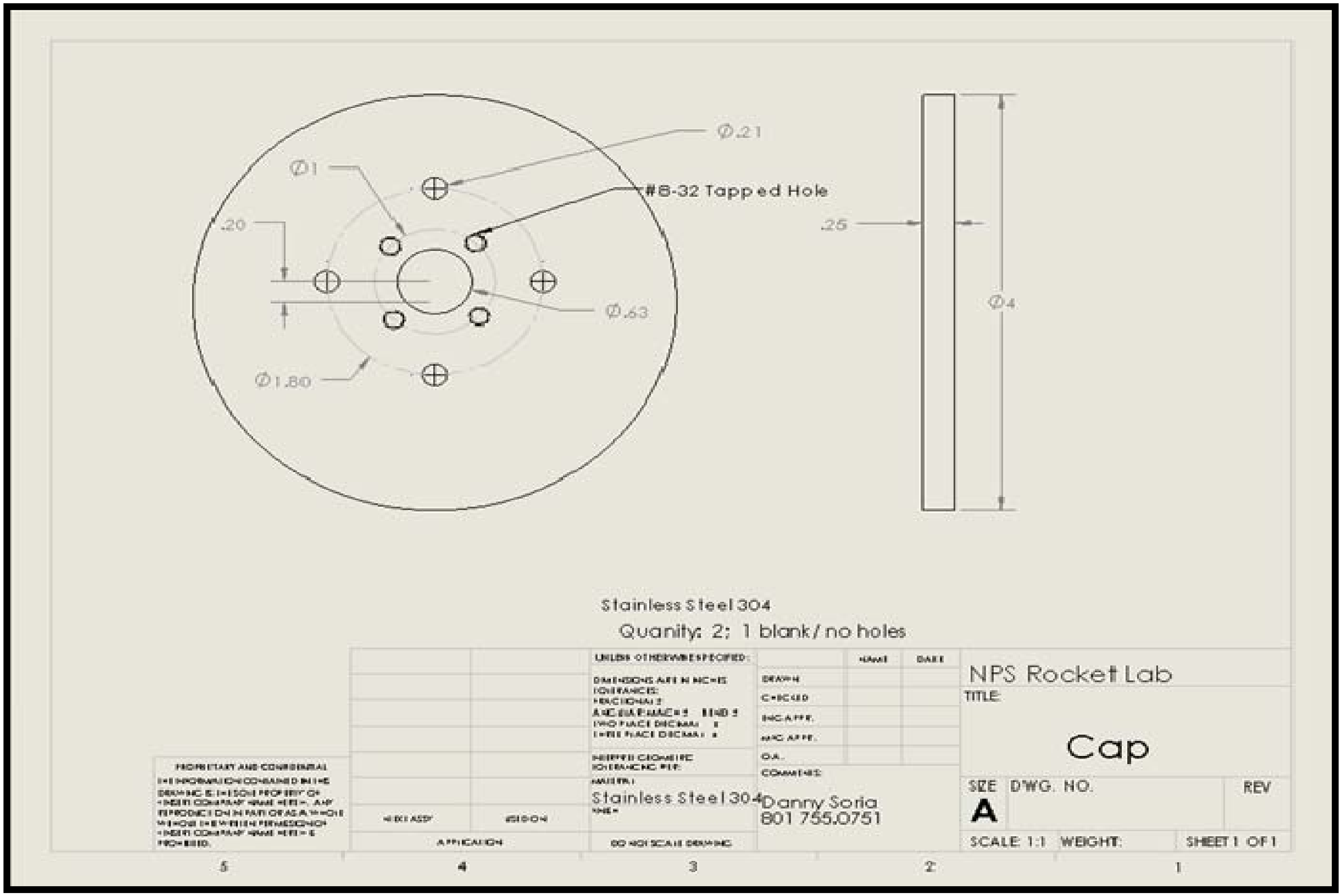

Holes are located on only the top portion of the piece
Ø.141
R.5
30°
.125
Ø.6275
Ø.75
Ø1.248 (+.000 -.002)
Ø.125
.25
.5
A
45.000°
SECTION A-A
1 extra blank piece with no holes in the long hollow section
Stainless Steel 304
Quanity: 2
NPS Rocket Lab
TITLE:
Can_part2
Danny Soria
831.656.2327
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

E. INSULATOR



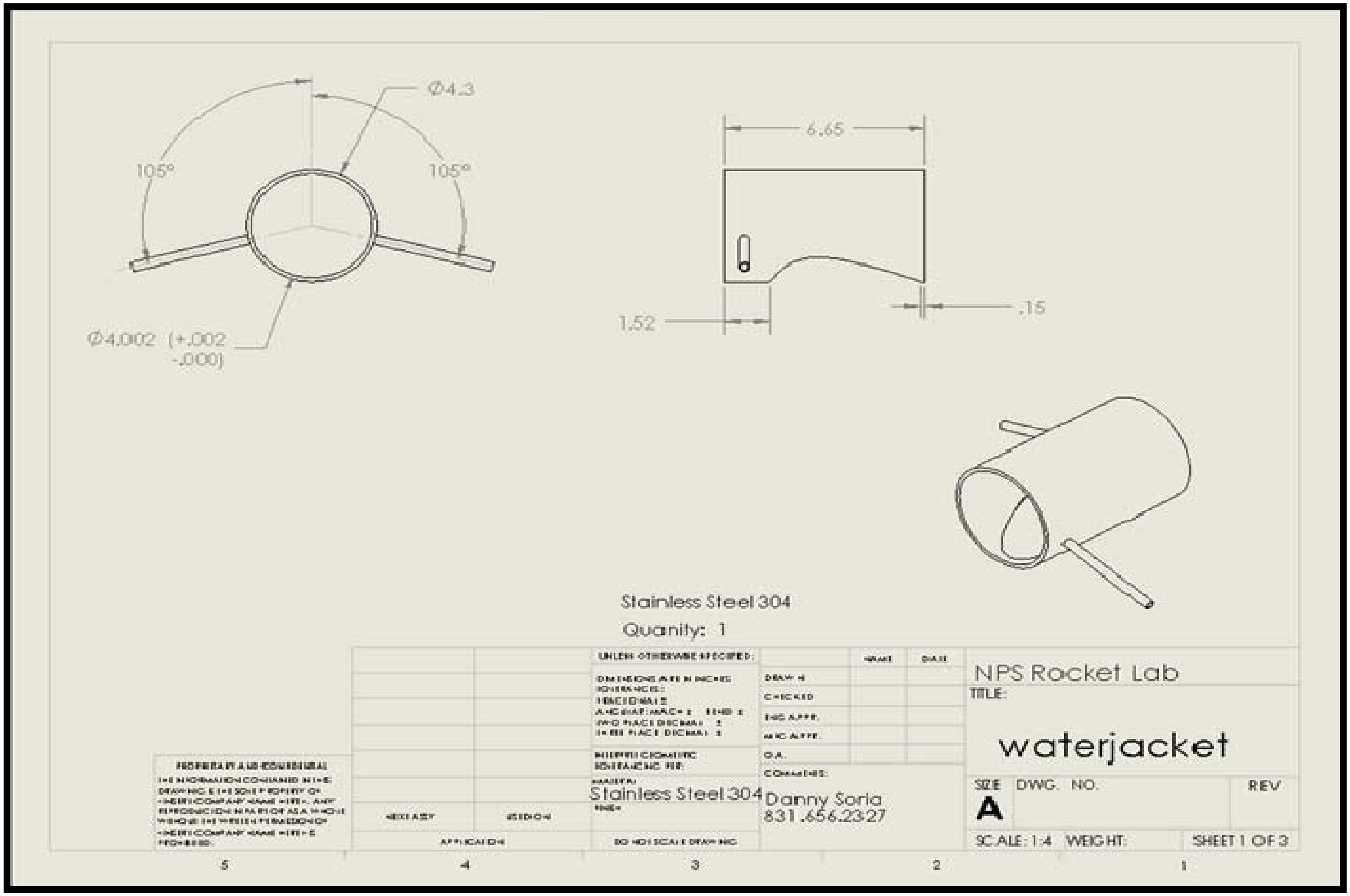
Ø1.059 (+.000 -.002)
4.14
1.650(+.000 -.002)
Ø0.75
Ø2.123(+.000 -.002)
Ø1.059 (+.000 -.002)
Ø0.21
Ø0.75
Ø1.80
Ø2.123 (+.000 -.002)
Teflon
Quanity: 2
NPS Rocket Lab
TITLE:
insulator
Teflon
Danny Soria
831.656.2327
SIZE A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

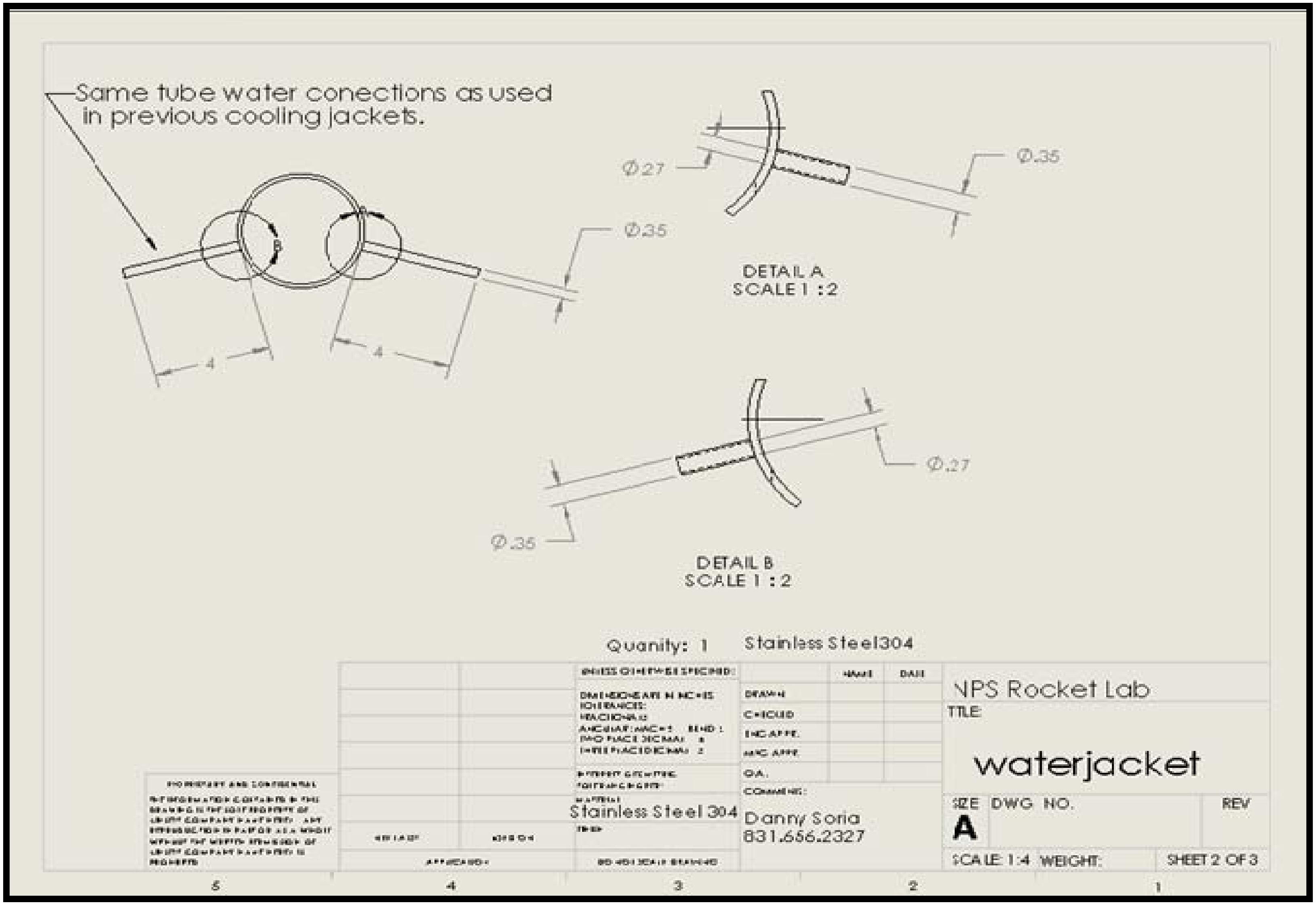
F. CAP



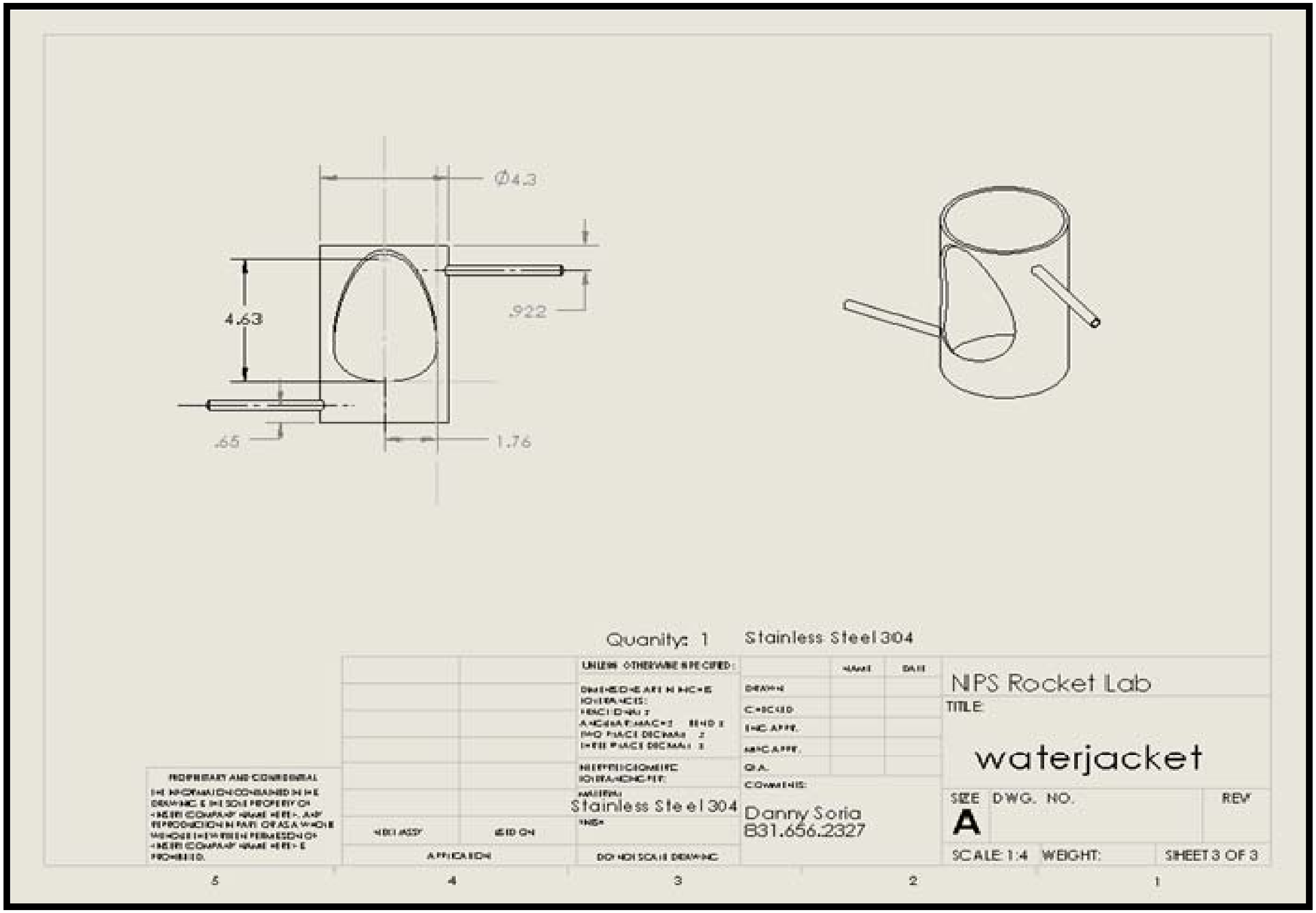
Ø.21
Ø1
#8-32 Tapped Hole
.20
.25
Ø.63
Ø4
Ø1.80
Stainless Steel 304
Quanity: 2; 1 blank/ no holes
NPS Rocket Lab
TITLE:
Cap
SIZE DWG. NO.
A
REV
SCALE: 1:1 WEIGHT:
SHEET 1 OF 1
Danny Soria
801 755.0751
Stainless Steel 304
PROPRIETARY AND CONFIDENTIAL
APPLICATION
DO NOT SCALE DRAWING

G. INLET WATER JACKET

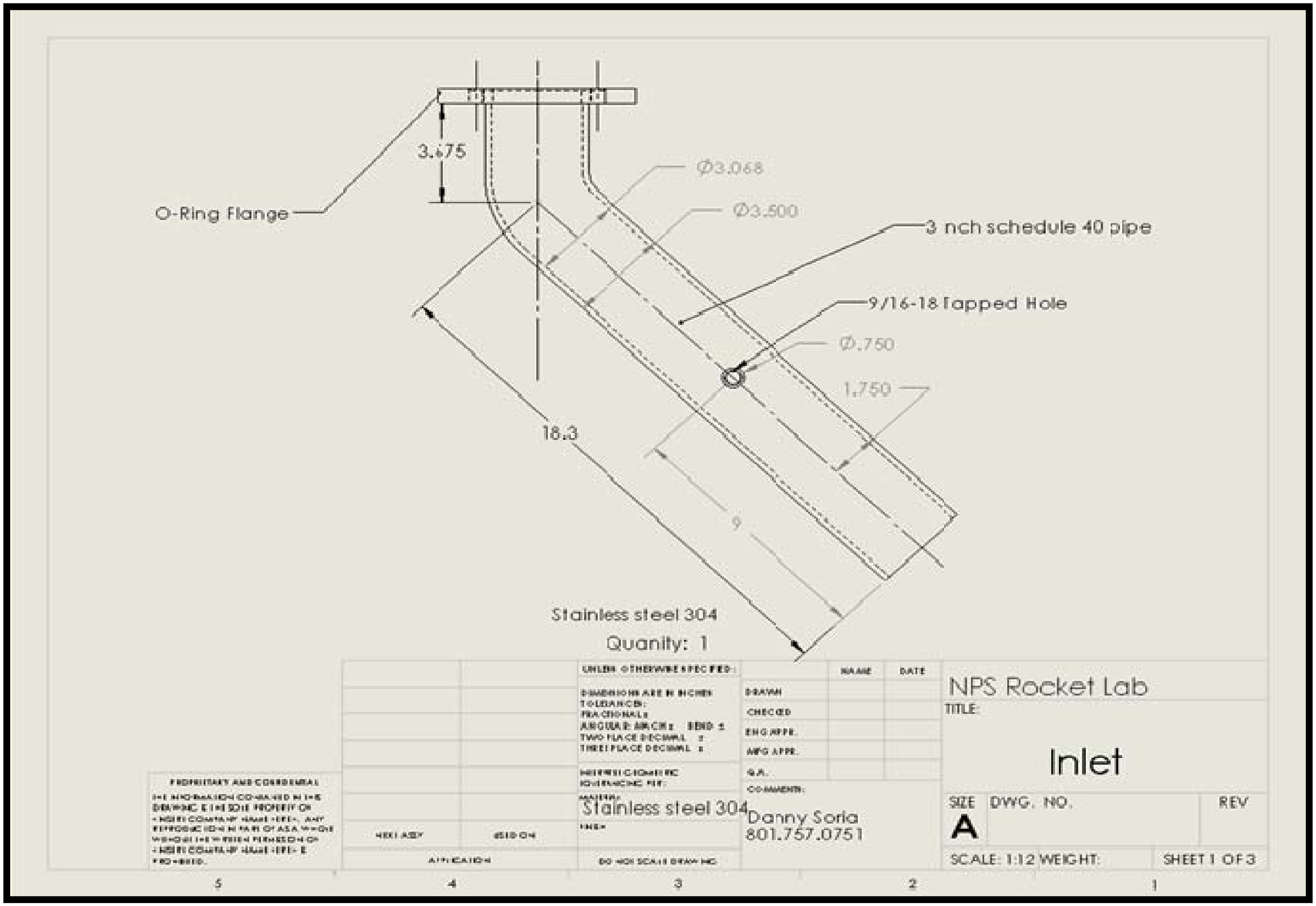


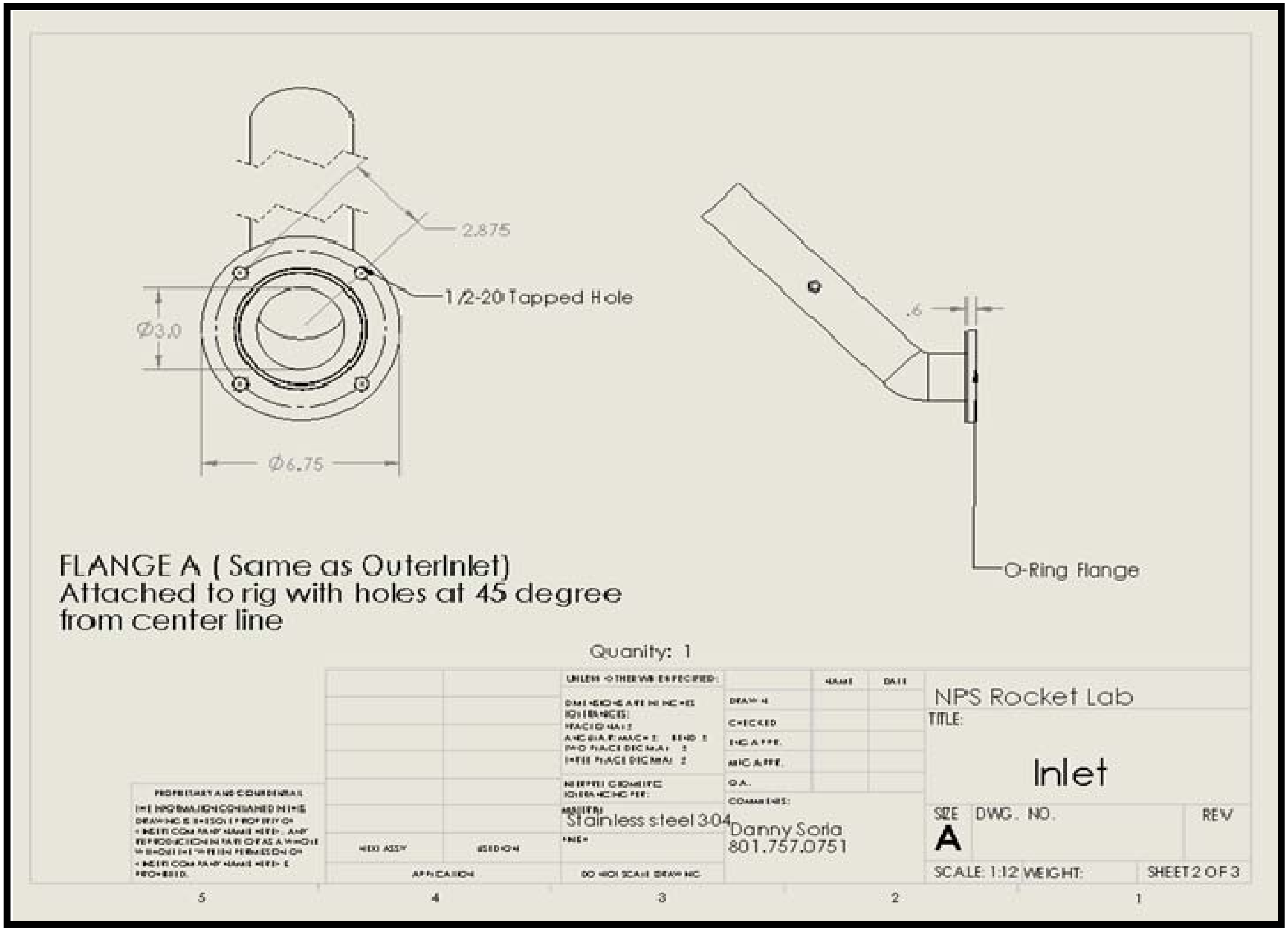


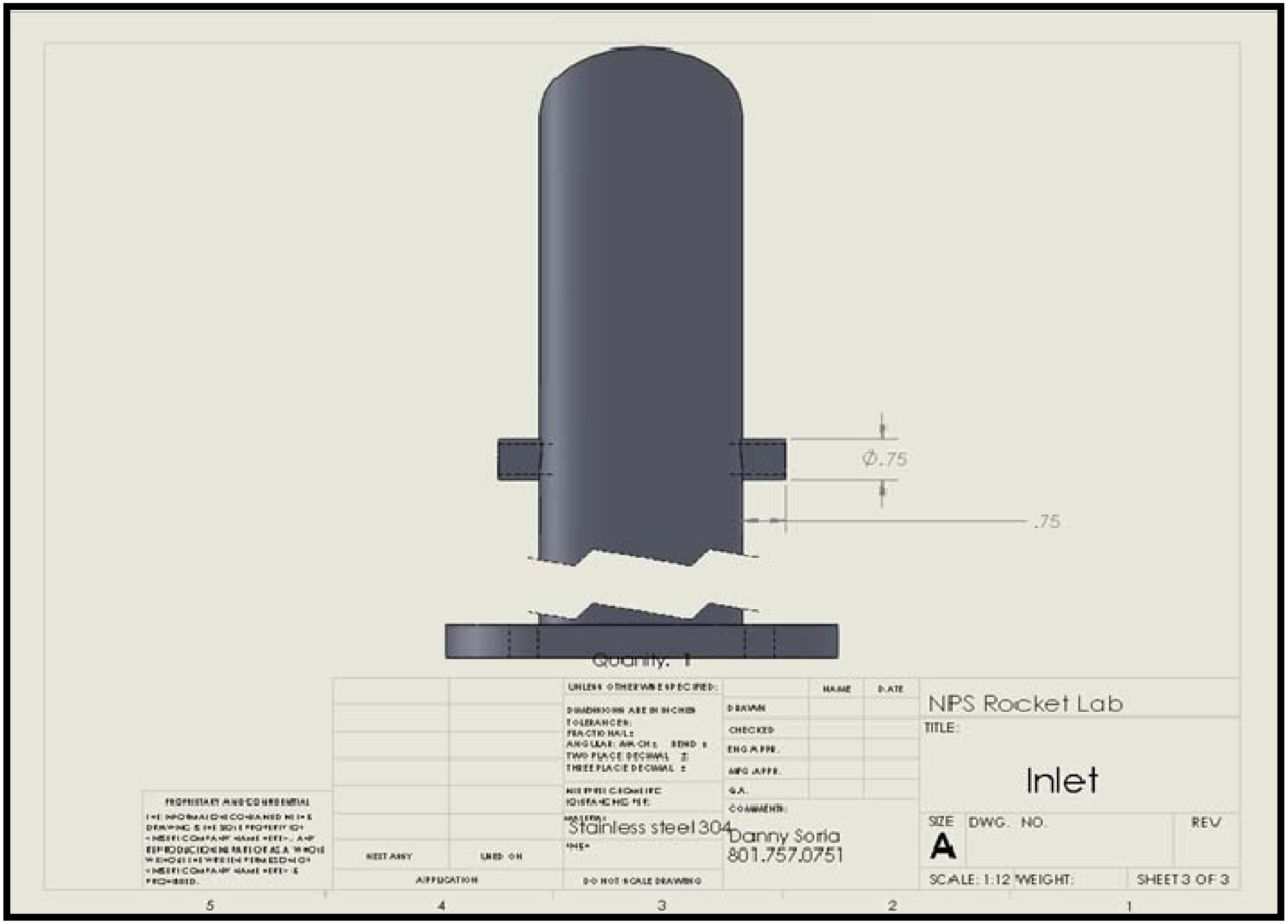
Same tube water conections as used in previous cooling jackets.
Ø.27
Ø.35
DETAIL A
SCALE 1 : 2
Ø.35
4
4
Ø.27
Ø.35
DETAIL B
SCALE 1 : 2
Quanity: 1
Stainless Steel304
Stainless Steel 304
Danny Soria
831.656.2327
NPS Rocket Lab
TITLE:
waterjacket
SIZE DWG NO.
A
REV
SCALE 1:4 WEIGHT:
SHEET 2 OF 3


Ø4.3
.922
4.63
.65
1.76
Quanity: 1
Stainless Steel 304
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
Stainless Steel 304
Danny Soria
831.656.2327
NIPS Rocket Lab
TITLE:
waterjacket
SIZE
A
DWG. NO.
REV
SCALE 1:4
WEIGHT:
SHEET 3 OF 3
5
4
3
2
1

H. FUEL INJECTION TUBE

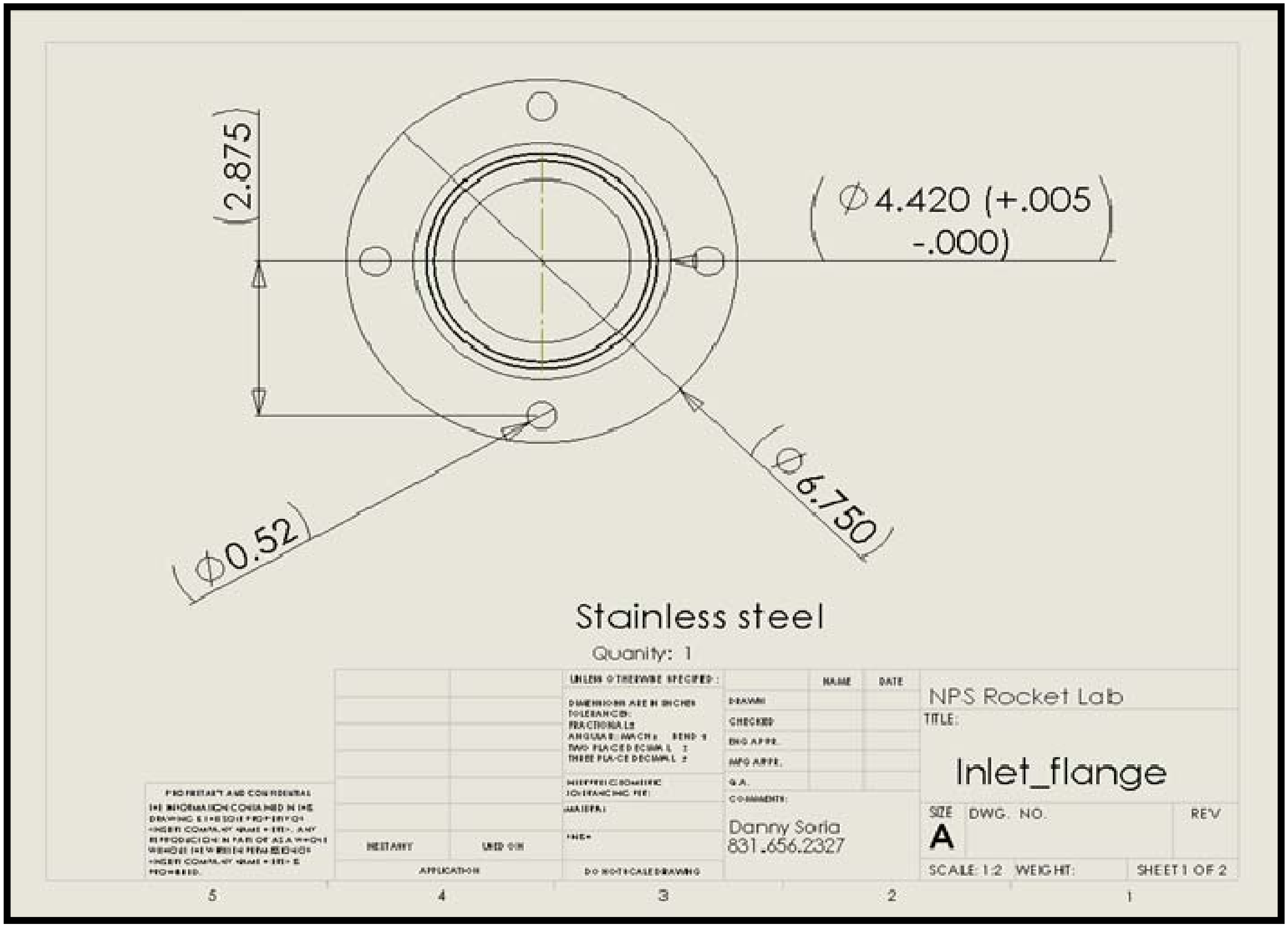


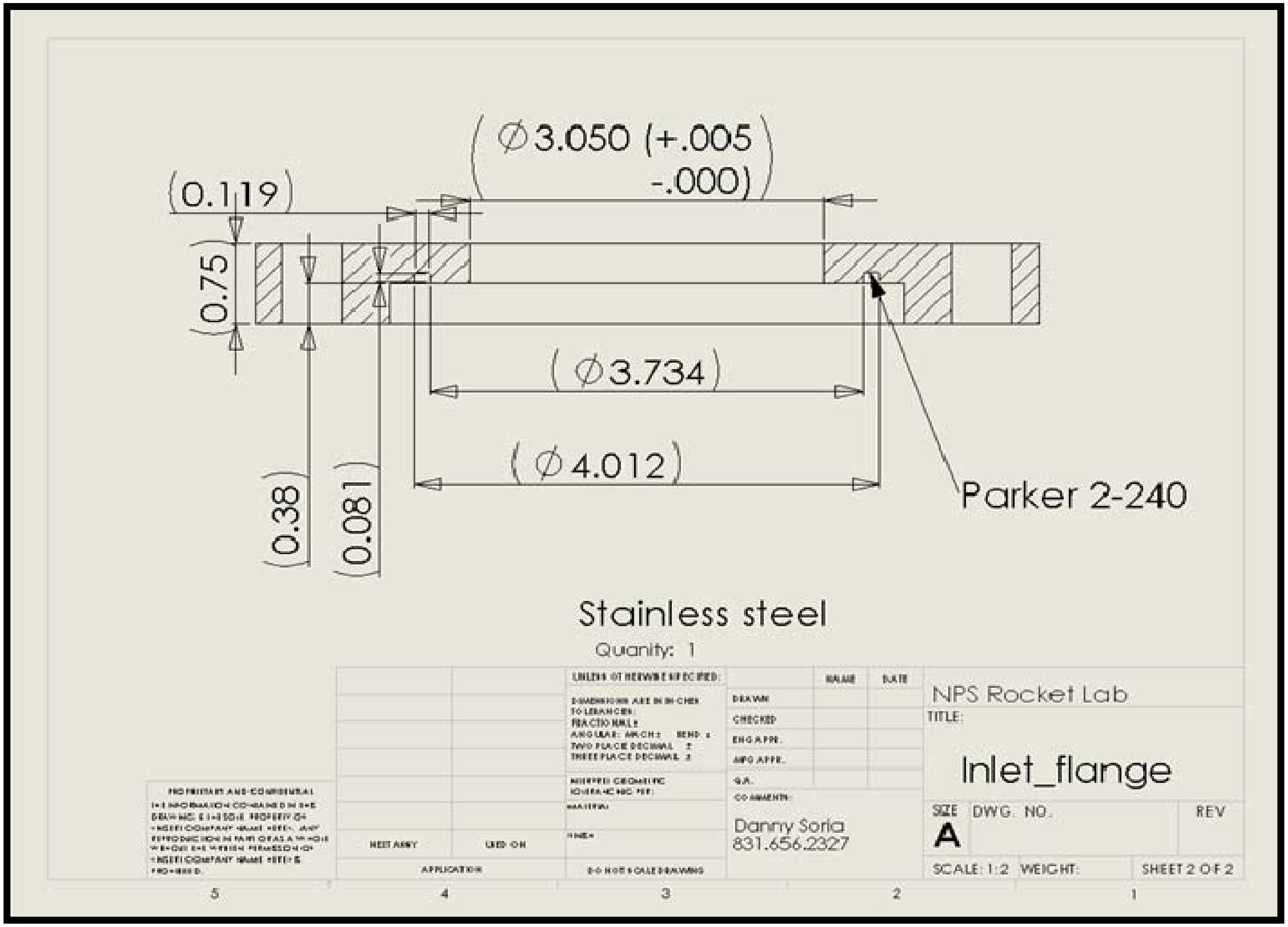

2.875
1/2-20 Tapped Hole
⌀3.0
⌀6.75
.6
O-Ring Flange
FLANGE A (Same as OuterInlet)
Attached to rig with holes at 45 degree
from center line
Quanity: 1
NPS Rocket Lab
TITLE:
Inlet
Stainless steel 304
Danny Soria
801.757.0751
SIZE A
DWG. NO.
REV
SCALE: 1:12
WEIGHT:
SHEET 2 OF 3



Ø.75
.75
Quantity: 1
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
NPS Rocket Lab
TITLE:
Inlet
DIMENSIONS ARE IN INCHES
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
Stainless steel 304
Danny Soria
801.757.0751
SIZE
A
DWG. NO.
REV
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
SCALE: 1:12
WEIGHT:
SHEET 3 OF 3

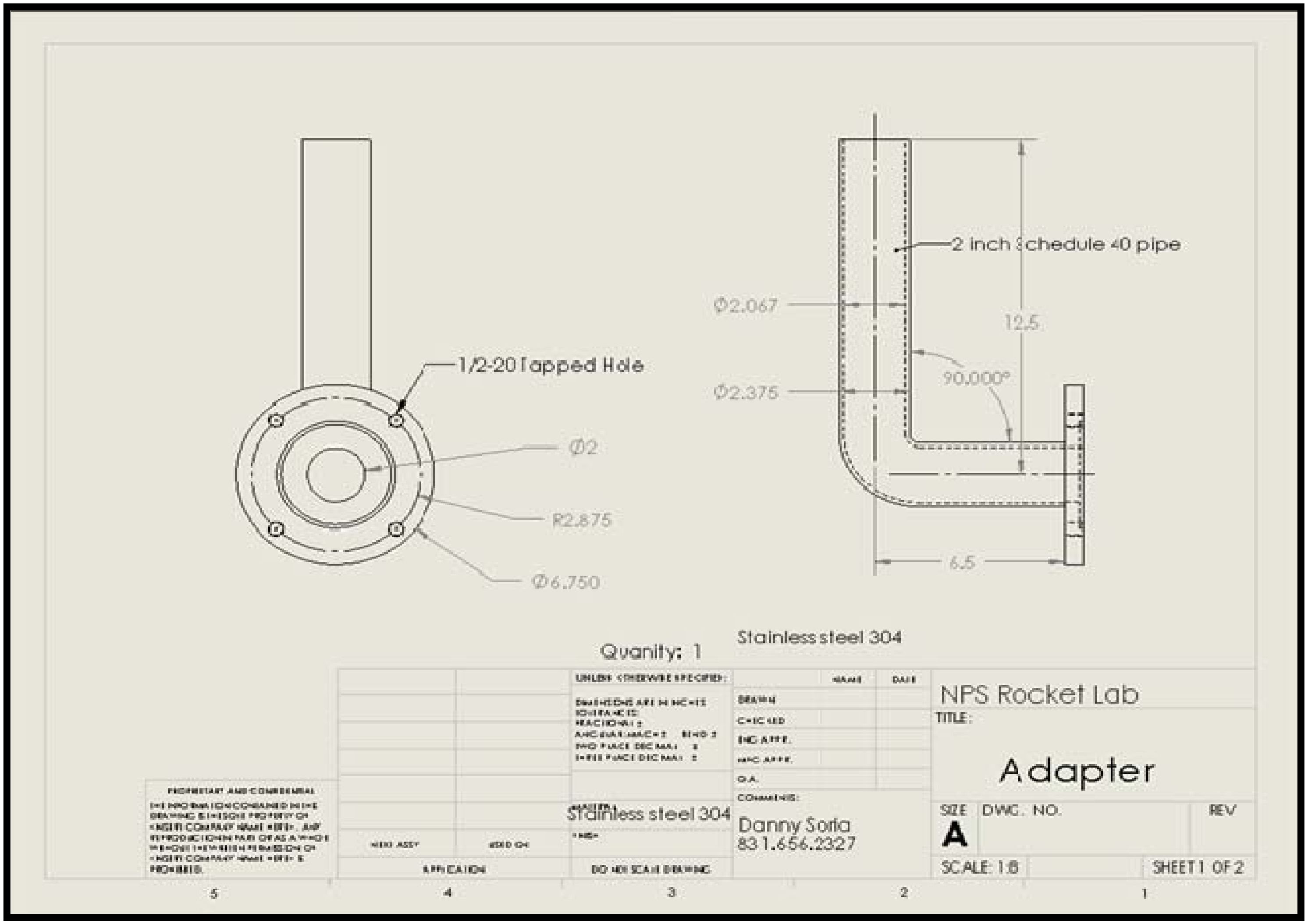
I. FLANGE FOR FUEL INJECTION TUBE

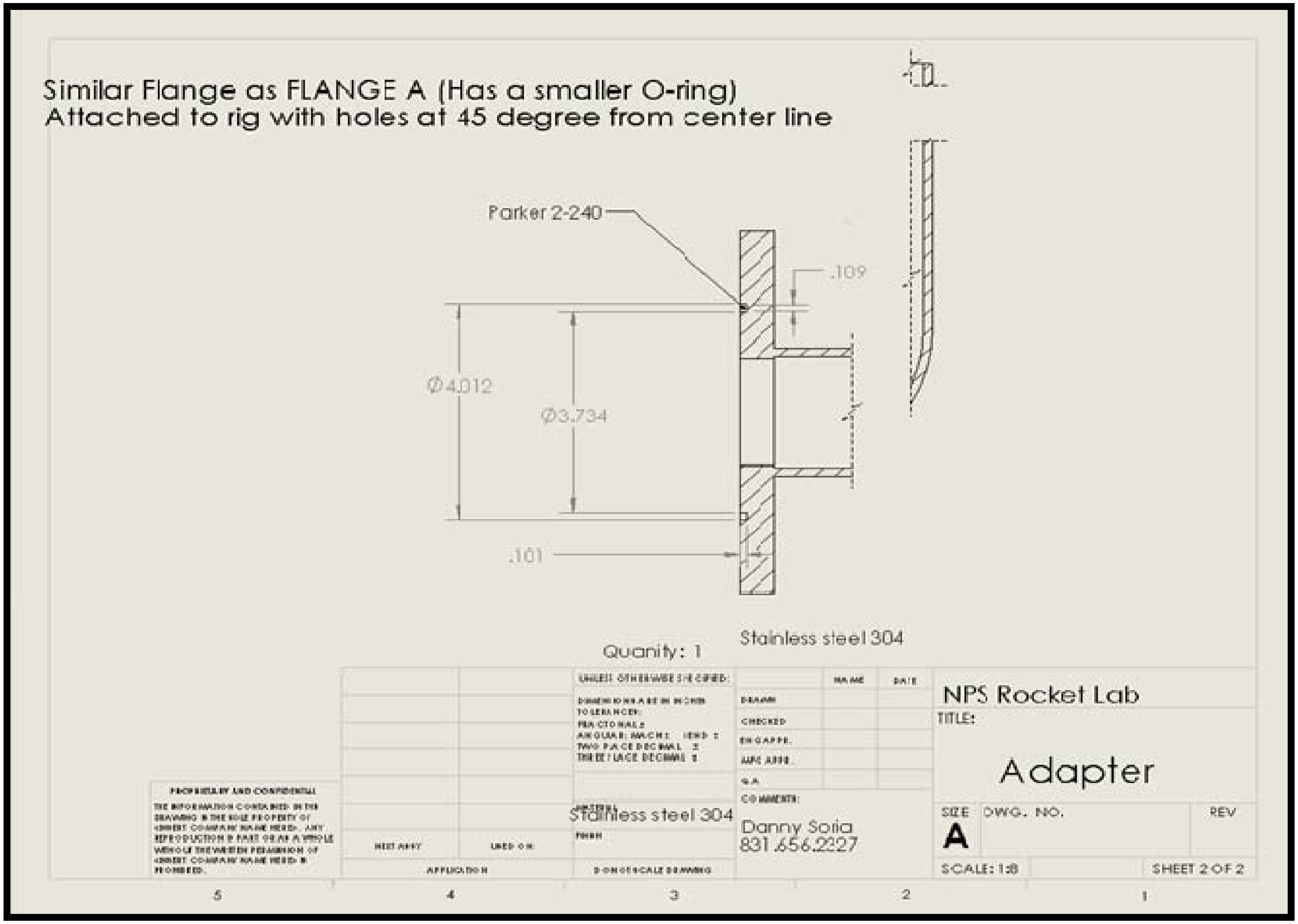




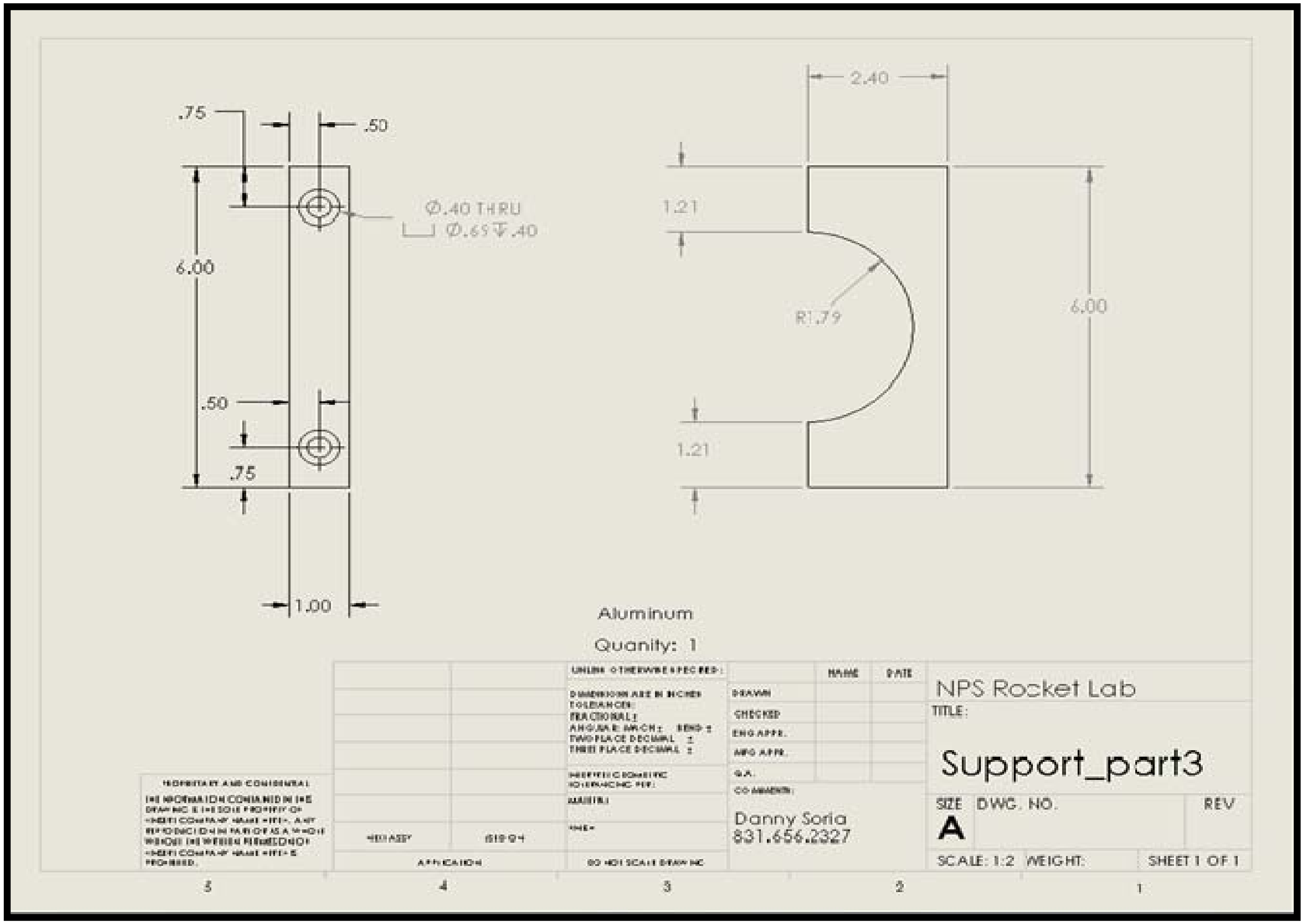
Ø3.050 (+.005 -.000)
0.119
0.75
Ø3.734
Ø4.012
Parker 2-240
0.38
0.081
Stainless steel
Quanity: 1
NPS Rocket Lab
TITLE:
Inlet_flange
Danny Soria
831.656.2327
SIZE A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 2 OF 2
NAME
DATE
DRAWN
CHECKED
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

J. RIG ADAPTOR

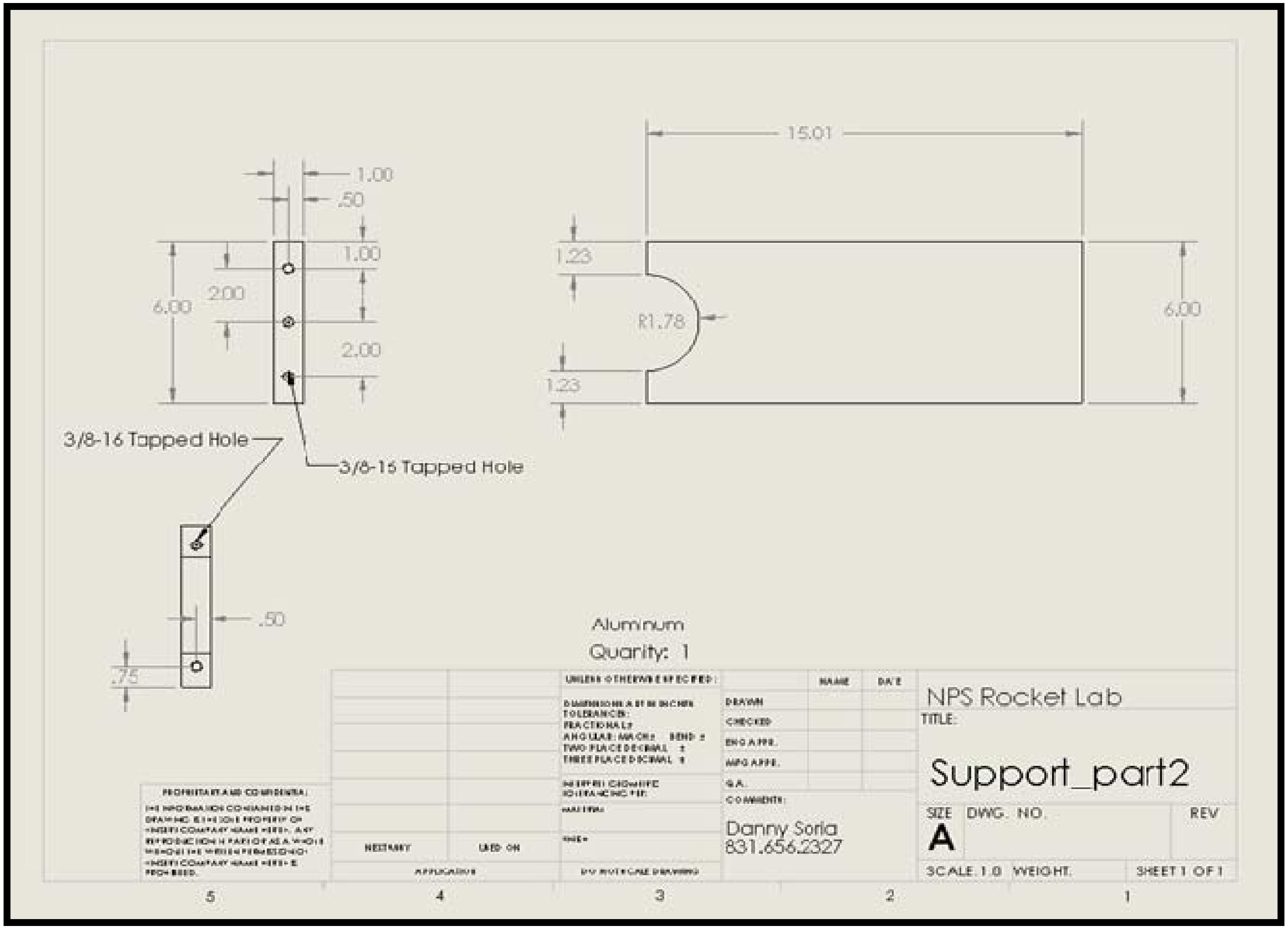


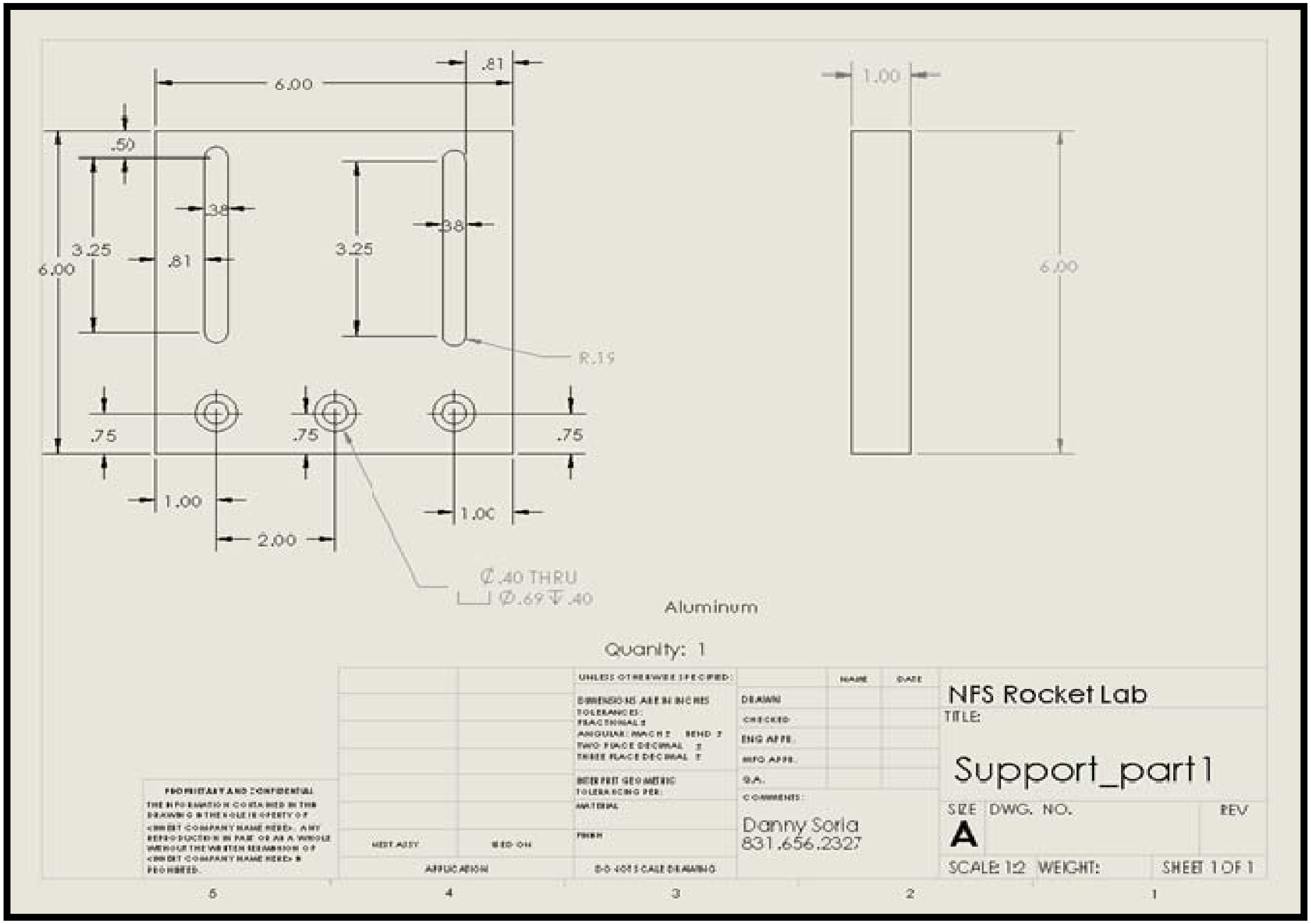

Similar Flange as FLANGE A (Has a smaller O-ring)
Attached to rig with holes at 45 degree from center line
Parker 2-240
.109
Ø4.012
Ø3.734
.101
Stainless steel 304
Quanity: 1
NPS Rocket Lab
TITLE:
Adapter
SIZE
A
DWG. NO.
REV
Stainless steel 304
Danny Soria
831.656.2327
SCALE: 1:8
SHEET 2 OF 2

K. RIG MOUNT



.75
.50
6.00
Ø.40 THRU
⌴ Ø.65 ↧ .40
.50
.75
1.00
2.40
1.21
R1.79
6.00
1.21
Aluminum
Quanity: 1
NPS Rocket Lab
TITLE:
Support_part3
Danny Soria
831.656.2327
SIZE A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


1.00
.50
1.00
6.00
2.00
2.00
15.01
1.23
R1.78
6.00
1.23
3/8-16 Tapped Hole
3/8-16 Tapped Hole
.50
.75
Aluminum
Quantity: 1
NPS Rocket Lab
TITLE:
Support_part2
Danny Soria
831.656.2327
SIZE
A
DWG. NO.
REV
SCALE 1:8
WEIGHT:
SHEET 1 OF 1



6.00
.81
1.00
.50
.38
3.25
.81
6.00
R.15
.75
1.00
2.00
1.00
⌀.40 THRU
⌴ ⌀.69 ↧ .40
Aluminum
Quanity: 1
NFS Rocket Lab
TITLE:
Support_part1
Danny Soria
831.656.2327
SIZE DWG. NO.
A
REV
SCALE: 1:2 WEIGHT:
SHEET 1 OF 1
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5. LT Danny Soria
   Naval Postgraduate School
   Monterey, California